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Bureau of Mines Information Circular/1985

Cobalt Availability—Market Economy Countries

A Minerals Availability Program Appraisal

By C. P. Mishra, C. D. Sheng-Fogg, R. G. Christiansen, J. F. Lemons, Jr., and D. L. De Giacomo

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Donald Paul Hodel, Secretary

BUREAU OF MINES
Robert C. Horton, Director

Library of Congress Cataloging in Publication Data

Cobalt availability—market economy countries.

(Bureau of Mines information circular; 9012)

Bibliography: p. 31

Supt. of Docs. no.: I 28.27:

1. Cobalt industry. 2. Cobalt mines and mining. I. Mishra, C. P. (Chamundeshawari P.) II. Series: Information circular (United States. Bureau of Mines); 9012.

~~TN295.U4~~ 622 s [338.2'748] 84-600271
[HD9539.C462]

PREFACE

In order to assess the availability of nonfuel minerals, the Bureau of Mines Minerals Availability Program collects, compiles, and evaluates information on producing, developing, and explored properties and mineral processing plants worldwide. Objectives are to classify domestic and foreign resources, identify by cost evaluation resources that are reserves, and prepare mineral availability analyses.

This report is one of a continuing series of minerals availability reports that analyze the availability of 34 commodities from domestic and foreign sources. Questions about the program should be addressed to Chief, Division of Minerals Availability, Bureau of Mines, 2401 E St., N.W., Washington, DC 20241.

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	lb	pound
g/L	gram per liter	m	meter
kg/m^2	kilogram per square meter	pct	percent
km	kilometer	tr oz	troy ounce

NOTE: Throughout the report, "ton" refers to the metric ton (2,204.6 lb) unless otherwise indicated.

COBALT AVAILABILITY—MARKET ECONOMY COUNTRIES

A Minerals Availability Program Appraisal

By C. P. Mishra,[1], C. D. Sheng-Fogg,[2] R. G. Christiansen,[3]
J. F. Lemons, Jr.,[1] and D. L. De Giacomo[4]

ABSTRACT

The Bureau of Mines performed a study of the availability of cobalt from market economy countries. The study entailed the detailed analysis of 97 deposits which contain 3.9 billion lb of cobalt at the demonstrated level; in 94 of the deposits cobalt is recovered as a byproduct, and in 3 it is considered the primary product. Since 97 pct of all recoverable cobalt is derived as a byproduct from copper and nickel deposits, the report focused on these two sources. At an assumed market price of $0.89/lb for copper, $3.45/lb for nickel, $475/tr oz for platinum, and $7/lb for cobalt, 1,330 million lb of cobalt at the demonstrated level are potentially available. This total includes 1,105 million lb of cobalt from copper properties, 190 million lb from nickel, 29 million lb from platinum, and 6 million lb from primary cobalt. This analysis indicates that the production cost for 589 million lb of cobalt can be totally covered by the revenues obtained from the other metals produced. The impacts of increases in capital investment and energy costs are also discussed.

[1]Supervisory physical scientist.
[2]Physical scientist.
[3]Mining engineer.
[4]Metallurgical engineer.
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INTRODUCTION

Cobalt is considered to be a critical commodity for the United States, owing to its extensive use in the aviation, manufacturing, and defense industries. Cobalt forms alloys that have heat and wear resistance, high strength, and superior magnetic properties. Despite its strategic importance, there is no current domestic primary production of cobalt; the United States must rely upon undependable foreign sources for much of its supply. As of 1982, approximately 48 pct of the cobalt used in the United States came from Zaire and Zambia(*1*).[5] These areas have proven to be unstable sources of supply, as illustrated by the 1978 disruption of the cobalt supply from Zaire due to insurgent activity.

Because of the critical nature of cobalt and the unstable sources of supply, it is important to examine the availability of cobalt from both present and potential alternative sources. This report examines the potential availability of cobalt from market economy countries.[6] The evaluation identifies the geological sources, as well as the technicalogical and economic factors that affect cobalt availability.

Cobalt is generally recovered as either a byproduct or coproduct of primary copper, nickel, or platinum production. In the case of nickel, cobalt availability is further related to the nickel product produced since cobalt is often not recovered in ferronickel production. Initially, 141 properties were reviewed for possible detailed availability analysis. The final list of properties selected for further examination consisted of 3 primary cobalt deposits and 94 properties that contain cobalt as a byproduct. The final list excluded nickel laterite deposits where cobalt assays are not defined and those instances where cobalt is not recovered from ferronickel production. Cobalt lost due to production of ferronickel is discussed later in the report.

In situ resources in this study are compared with resource estimations of other publications. Resources are expressed in terms of in situ tons.[7]

Recoverable cobalt is reported as metal in millions of pounds. Previous studies that estimated worldwide resources of cobalt include work by the National Materials Advisory Board (*2*), Wyllie (*3*), and the Bureau of Mines (*4*). The resource estimates in this study and the previous studies are generally comparable, as discussed later in this report. Differences are attributed to varying cutoff grades and additional or updated data used in this study.

An economic evaluation of each deposit was performed to determine its cost of production, which includes a 15-pct discounted cash flow rate of return (DCFROR). The DCFROR is commonly defined as the rate of return that makes the present worth of cash flow from an investment equal to the present worth of all after-tax investments. These individual deposit analyses were than aggregated into availability curves that relate the total cost of production to the potential recoverable commodities. The study investigated the interrelationship of the recovery of cobalt and its associated primary commodities copper, nickel, and platinum.

The impact of energy cost on the availability of cobalt is presented in the report. Also included is a study on the effect of increase in capital investment costs on potential cobalt availability.

COBALT USE AND PRODUCTION

The availability of cobalt is of vital importance to numerous industries due to its use in alloys, coatings, nonmetallic oxides, and other compounds. The primary use of cobalt is in superalloys for aircraft and surface engine parts which are required to endure stress at high temperatures. Because cobalt retains its magnetic properties to 1,121° C, it is widely used in permanent magnets, particularly in the electrical equipment industry. Cobalt alloys are utilized in machinery, primarily in cutting tools, which require very high strength and abrasion resistance. Cobalt also serves as the metal matrix (cement) for various carbides known as cemented carbides. Cemented carbide bits are used in drilling and mining operations. Coatings of cobalt alloys impart resistance to abrasion, heat, impact, and corrosion, and are thus used in many industries to improve material performance.

The major uses of nonmetallic cobalt compounds are in paints, ceramics, glass, and chemicals. Cobalt oxides and organic compounds are used as drying agents in paints and ceramics and also serve as decolorizers, dyes, pigments, and oxidizers. In the form of a ground coat frit, cobalt promotes the adherence of enamel to steel; in organic compounds, it is used to improve the adherence of steel to rubber in steel-belted radial tires. In chemical processes, cobalt is used primarily as a catalyst in hydrogenation, but it is also useful in hydration, desulfurization, oxidation, reduction, and synthesis of hydrocarbons. Cobalt can be added to soils as a nutritive agent.

In 1981, the total U.S. consumption of cobalt was 11.7 million lb, of which superalloys accounted for 4.2 million lb, or 36 pct. Use of cobalt in magnetic alloys was 1.7 million lb of cobalt, 14 pct of total U.S. consumption. Use of cobalt as a drier, catalyst, or wear-resistant material accounted for the majority of the remaining consumption of the metal in the United States. Table 1 summarizes the domestic consumption of cobalt by end use for the years 1979-81.

Total world cobalt production in 1981 was 56 million lb. A breakdown by country is shown in table 2. Current cobalt supply is highly dependent on the production from Zaire and Zambia, which supplied 62.5 pct of the total world production as a byproduct of copper recovery. Finland also recovers cobalt as a byproduct of copper operations. Other sources of cobalt from market economy countries include

[5]Italicized numbers in parentheses refer to items in the list of references preceding the appendix.

[6]Market economy countries, as defined by the Bureau of Mines, include all countries except Albania, Bulgaria, China, Cuba, Czechoslovakia, the German Democratic Republic, Hungary, Kampuchea, North Korea, Laos, Mongolia, Poland, Romania, the U.S.S.R., and Vietnam.

[7]In this report "ton" refers to the metric ton (2,204.6 lb) except where otherwise indicated.

TABLE 1.—U.S. consumption of cobalt by end use, 1979-81
(Thousand pounds of contained cobalt)

Use	1979	1980	1981
Steel:			
Stainless and heat resisting	137	47	35
Full-alloy	227	116	141
High-strength low-alloy	W	W	W
Tool	413	321	170
Superalloys	5,276	6,285	4,195
Alloys (excludes alloy steels and superalloys):			
Cutting and wear-resistant materials[1]	2,123	1,344	1,076
Welding materials (structural and hard-facing)	444	620	488
Magnetic alloys	3,266	2,267	1,687
Nonferrous alloys	392	150	131
Other alloys	274	210	123
Mill products made from metal powder	W	W	W
Chemical and ceramic uses:			
Pigments	199	282	329
Catalysts	1,882	1,656	1,279
Ground coat frit	554	482	441
Glass decolorizer	43	40	40
Drier in paints or related usage	[2]1,791	1,331	1,378
Feed or nutritive additive	NA	75	58
Miscellaneous and unspecified	381	95	109
Grand total	[2]17,402	15,321	11,680

NA Not available. W Withheld to avoid disclosing company proprietary data; included in "Miscellaneous and unspecified".

[1]Includes cemented and sintered carbides and cast carbide dies or parts.
[2]Includes drier and feed usage.

Source: References 5-6.

TABLE 2.—World cobalt production by country, 1981[P]

Country	Metal content[1] of mine output, tons	Metal content or pct of total mine output	Metal recovered,[2] tons
Zaire	[e]15,504	51.2	[e]11,124
Zambia	3,416	11.3	2,570
U.S.S.R.	2,250	7.4	3,847
Canada	2,080	6.9	910
Australia	[r e]1,996	6.6	NAp
Cuba	1,715	5.7	NAp
Finland	1,034	3.4	1,229
Philippines	997	3.3	NAp
Morocco	789	2.6	NAp
Botswana	254	.8	NAp
New Caledonia	141	.5	NAp
Zimbabwe	110	.3	93
Japan	NAp	NAp	2,421
Norway	NAp	NAp	1,444
France	NAp	NAp	447
United Kingdom[3]	NAp	NAp	[e]726
Germany, Federal Republic of	NAp	NAp	[e]399
United States	NAp	NAp	406
Total[4]	30,276	100	25,616

[e]Estimated. [P]Preliminary. [r]Revised. NAp Not applicable.

[1]Figures represent cobalt content in mined ore.
[2]Figures represent elemental cobalt recovered unless otherwise specified. In addition to the countries listed, Czechoslovakia presumably recovers cobalt from Cuban nickel concentrates. Belgium has imported small quantities of partly processed materials containing cobalt, but available information is inadequate for reliable estimates of cobalt recovery from these materials.
[3]Estimated recovery of elemental cobalt in refined cobalt oxides and salts from intermediate metallurgical products originating in Canada.
[4]In addition to the countries listed, Bulgaria, Cyprus, the German Democratic Republic, Greece, Indonesia, Poland, the Republic of South Africa, Spain, and Uganda are known to produce ores that contain cobalt. Information is inadequate for reliable estimates of output levels. Other copper- and/or nickel-producing nations may also produce ores containing cobalt, but recovery is small or nil.

Source: Reference 1.

recovery from nickel sulfide deposits in Canada, Botswana, and Zimbabwe; nickel laterite deposits in the Philippines and New Caledonia; both nickel sulfide and laterite deposits in Australia; and one high-grade cobalt deposit in Morocco.

EVALUATION METHODOLOGY

The procedures followed in the evaluation of cobalt availability from deposit identification to development of economic availability information are illustrated in figure 1. In this study, 3 primary cobalt, 4 platinum, 24 copper, and 110 nickel properties that contain demonstrated amounts of cobalt were investigated. Evaluations of domestic properties were performed at Bureau of Mines Field Operations Centers located in Denver, CO, Juneau, AK, Pittsburgh, PA, and Spokane, WA. Foreign deposits were evaluated by private companies under contract to the Bureau.

A total of 97 deposits were selected for detailed study: 3 primary cobalt deposits, 4 platinum deposits, 17 copper-cobalt deposits, and 73 nickel-cobalt deposits. Table 3 lists the deposits selected for detailed evaluation. Potential cobalt sources investigated but not included in this study are listed in the appendix.

The analysis methodology employed in this study follows:

1. Resource quantities and grades as of January 1981 were evaluated for each selected deposit in relation to the physical parameters of the ore body and technological limitations of recovery methods. All technologies are based on current industry practice.
2. Capital, operating, and transportation costs for mining, concentrating, and postmill processing methods were estimated for each producing or proposed project.
3. Two economic evaluations were performed to identify the relationship of cobalt and primary commodity availability at each property.

The first analysis determined the net total cost of cobalt production, after assuming all other commodities were sold at representative 1981 prices. A low average total cobalt cost after these credits indicates a property where revenues generated by other commodities are sufficient to cover their own production cost as well as part or all of the cost of cobalt production. A high average total cost after these credits indicates a property where the revenues from other commodities are not sufficient to cover either their own production cost or the cost of producing cobalt.

In the second analysis, cobalt and other commodities, except the primary commodity, are assumed to be sold at 1981 prices, and the average total cost of the primary commodity is determined. This average total cost can be com-

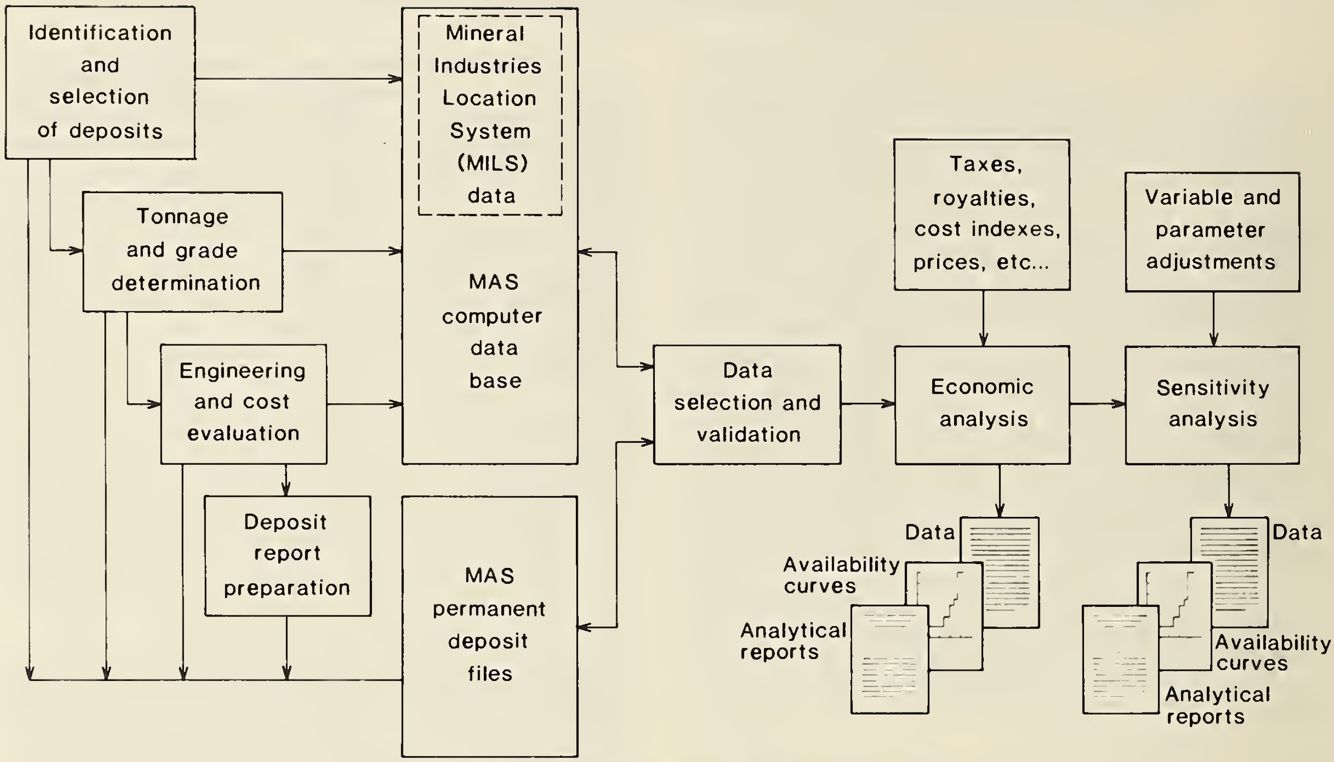


Figure 1.—Minerals availability program workflow.

pared with an expected long-term market price for the primary commodity to evaluate if the resources can be economically recovered.

4. Upon completion of individual property analyses, properties with the same primary commodity were aggregated to provide an overall assessment of potential availability of cobalt as a byproduct of that primary commodity.

Resource estimates were based upon current recovery technology and data obtained from a number of sources: Bureau of Mines, U.S. Geological Survey, State publications, professional journals, industry publications, company annual and 10K reports, and data made available to the Bureau by private companies. The knowledge and expertise of personnel from Government agencies and industry were also utilized. Adjustments were made to data to reflect January 1981 resources. For this study, only demonstrated resources were considered. Demonstrated resources, as defined by the U.S. Geological Survey and the Bureau of Mines (*8*), include measured plus indicated tonnages where quantities are computed from site inspection, including outcrops, trenches, mine workings, and drill holes, and whose grades are computed from sampling.

Capital costs for exploration, acquisition, development, and mine and mill plant and equipment were estimated. The total capital expenditure for each of the different mining and processing facilities includes the costs of mobile and stationary equipment, construction of engineering facilities and utilities, and working capital. Environmental costs were included when known. Facilities and utilities (infrastructure) is a broad category that includes the cost of access and haulage facilities, water facilities, power supply, and personnel accommodations. Working capital is a revolving cash fund required to cover operating expenses such as labor, supplies, taxes, and insurance.

For this study, all capital investments made 15 years prior to the date of analysis (January 1981) are assumed to be fully depreciated. For producing operations, book values of investments as of January 1981 were calculated, and all reinvestments and operating and transportation costs were estimated in January 1981 dollars. Capital and operating costs for undeveloped deposits were estimated in January 1981 dollars. All analyses were performed in constant dollars; therefore, no escalations of costs or prices were considered. All costs for foreign operations were converted to U.S. dollars using exchange rates to reflect U.S. dollar-equivalent costs of doing business within that foreign country.

Operating costs for each property were determined as a combination of direct, indirect, and miscellaneous operating costs. Direct operating costs include materials, utilities, production and maintenance labor, and payroll overhead. Indirect operating costs include technical, clerical, and administrative labor, facilities maintenance, supplies, and research. Miscellaneous costs include local taxes, insurance, deferred expenses, and loan payments.

An economic evaluation of each deposit was performed to determine its cost of production, based on an assumed 15-pct discounted cash flow rate of return (DCFROR) and the commodity prices shown in table 4. The DCFROR is commonly defined as the rate of return that makes the present worth of cash flow from an investment equal to the present worth of all after-tax investment (*9*). The average total cost of production determined by the Supply Analysis Model (SAM), a computerized modeling system developed by the Bureau, provides an estimate of what the average long-run price of the primary commodity must be to recover all costs of production, including a predetermined percent rate of return on investment (*10*).

A separate tax-records file in SAM, maintained for

TABLE 3.—List of evaluated properties with mining methods and ownership

Name of country and property	Status[1]	Ore type	Mining method	Owner
NICKEL-COBALT PROPERTIES				
Australia:				
Greenvale	P	Laterite	Surface	Metals Exploration Ltd., Freeport Exploration.
Kambalda	P	Sulfide	Underground	Western Mining Corp.
Mt. Keith	N	.. do ..	Surface	Metals Exploration Ltd., Freeport Exploration.
Botswana:				
Selebi/Phikwe	P	Sulfide	Surface, underground	BCL Ltd.
Brazil:				
Niquelandia (CNT)	P	Laterite	Surface	Companhia Niquel De Tocantins.
Niquelandia (Codemin)	N	.. do ..	do	CODEMIN.
Canada:				
Birchtree	N	Sulfide	Underground	Inco.
Bucko Lake	N	.. do ..	do	Bowden Lake Nickel Mines.
Clarabelle	P	.. do ..	Surface	Inco.
Copper Cliff North	N	.. do ..	Undergound	Do.
Copper Cliff South	P	.. do ..	do	Do.
Crean Hill	N	.. do ..	Surface	Do.
Creighton	P	.. do ..	Surface, underground	Do.
Falconbridge	P	.. do ..	Undergound	Falconbridge.
Falconbridge East	P	.. do ..	do	Do.
Frood	P	.. do ..	Surface, undergound	Do.
Fraser	P	.. do ..	Underground	Falconbridge.
Garson	P	.. do ..	do	Inco.
Key Lake	N	.. do ..	Surface	Key Lake Mining Corp.
Levack	P	.. do ..	Underground	Inco.
Little Stobie	P	.. do ..	Surface, underground	Do.
Lockerby	P	.. do ..	Underground	Falconbridge.
McCreedy West	P	.. do ..	Surface, underground	Inco.
Mystery Lake	N	.. do ..	Surface	Do.
Onaping-Craig	P	.. do ..	Surface, undergound	Falconbridge.
Pipe Surface	P	.. do ..	Surface	Inco.
Pipe Underground	N	.. do ..	Underground	Do.
Shebandowan	P	.. do ..	do	Do.
Soab	N	.. do ..	do	Do.
Stobie	P	.. do ..	Surface, underground	Do.
Strathcona	P	.. do ..	Underground	Falconbridge.
Thompson	P	.. do ..	do	Inco.
Totten	N	.. do ..	Surface, underground	Boliden AB and Timiskaming.
Guatemala: Exmibal	P	Laterite	Surface	Inco and Hanna.
India: Sukinda	N	.. do ..	do	Do.
Indonesia: Gag Island	N	.. do ..	do	P.T. Pacific Nickel.
New Caledonia:				
Goro	N	.. do ..	do	Inco.
Ile Art	N	.. do ..	do	Cofremni.
Kouaoua	P	.. do ..	do	Pentecost Nickel.
Moneo	P	.. do ..	do	CGMC/Ballande.
Nakety	P	.. do ..	do	Societe Le Nickel.
Nepoui	P	.. do ..	do	Do.
Ouaco	P	.. do ..	do	Do.
Ouinne	P	.. do ..	do	Societe G Montagnat.
Poro	P	.. do ..	do	Societe Le Nickel.
Poun	N	.. do ..	do	Cofremni.
Prony	N	.. do ..	do	Penamex.
Thio	P	.. do ..	do	Societe Le Nickel.
Tiebaghi	N	.. do ..	do	Cofremni.
Philippines:				
Infanta	P	.. do ..	do	Philippine Goernment.
Nonoc Mine	P	.. do ..	do	Marinduque Mining Corp.
Soriano	N	.. do ..	do	Soriano Corp.
United States:				
Alaska: Yakobi Island	N	Sulfide	Surface	Inspiration Development Co.
California:				
Gasquet	N	Laterite	do	California Nickel Corp.
Pine Flat area	N	.. do ..	do	Hanna Mining Corp.
Maine: Crawford Pond	N	Sulfide	do	Knox Mining Corp.

[1]P indicates mines producing in 1981 and N means nonproducing deposits.

TABLE 3.—List of evaluated properties with mining methods and ownership—Con.

Name of country and property	Status[1]	Ore type	Mining method	Owner
		NICKEL-COBALT PROPERTIES—Con.		
United States:—Con.				
Minnesota:				
Birch Lake	N	Sulfide	Surface	Inco U.S. Inc.—Hanna—Duval.
Birch Lake Underground[2]	N	.. do ..	Underground	Do.
Birch Lake Underground 1	N	.. do ..	do	Do.
Birch Lake Underground 2	N	.. do ..	do	Do.
Birch Lake Underground 3	N	.. do ..	do	Do.
Birch Lake Underground 4	N	.. do ..	do	Do.
Birch Lake Underground 5	N	.. do ..	do	Do.
Dunka River	N	.. do ..	Surface	AMAX.
Ely Spruce Underground	N	.. do ..	Underground	Inco.
Minnamax	N	.. do ..	do	AMAX.
Partridge River	N	.. do ..	Surface	U.S. Steel.
Spruce Pit Area	N	.. do ..	do	Inco U.S. Inc.—Hanna—Duval.
Oregon: Red Flat	N	Laterite	do	Hanna Mining Corp.
Puerto Rico: Guanajibo	N	.. do ..	do	Puerto Rico Government.
Zimbabwe:				
Trojan	P	Sulfide	Underground	Trojan Nickel Mine Ltd.
Empress	P	.. do ..	do	Rio Tinto Mining.
Shangani	P	.. do ..	do	Johannesburg.
		COPPER-COBALT PROPERTIES		
Finland:				
Keretti Mine	P	Sulfide	Underground	Outokumpu Oy.
Luikonlahti	P	.. do ..	do	Myllykoski Oy.
Vuonos Mine	P	.. do ..	do	Outokumpu Oy.
Uganda: Kilembe	N	Sulfide	do	Uganda Government.
United States:				
California: Grey Eagle	N	.. do ..	Surface	Noranda.
Missouri: Boss-Bixby	N	.. do ..	Underground	Getty Oil-Azcon-Hanna.
Zaire:				
Dikuluwe-Mashamba	P	.. do ..	Surface	Gecamines.
Kakanda-Diselle	P	.. do ..	do	Do.
Kambove	P	.. do ..	Underground	Do.
Kamoto Underground Mine	P	.. do ..	do	Do.
Kov Open Pit	P	.. do ..	Surface	Do.
Mutoshi Ruwe	P	.. do ..	do	
Tenke Fungurume	N	.. do ..	do	Do.
Zambia:				
Baluba	P	.. do ..	Underground	
Chibuluma	P	.. do ..	do	Zambian Consolidated Copper Mines, Ltd. (ZCCM).
Chingola Division	P	.. do ..	Surface, underground	Do.
Rokana Division	P	.. do ..	do	Do.
		PLATINUM-COBALT PROPERTIES		
South Africa:				
Der Brochen	N	Sulfide	Underground	Platinum Proprietary Ltd.
Impala	P	.. do ..	do	Impala Platinum Holdings Ltd.
Rustenburg	P	.. do ..	do	Rustenburg Platinum Ltd.
Western Platinum	P	.. do ..	do	Western Platinum Ltd.
Morocco: Bou Azzer[3]	P	Sulfide	do	Compagnie De Tifnout (CTT).
United States:				
Idaho: Blackbird	N	.. do ..	do	Noranda.
Missouri: Madison	N	.. do ..	do	Anschutz Corp.

[1]P indicates mines producing in 1981 and N means nonproducing deposits.
[2]The Birch Lake Underground area incorporates an extensive enough resource that 6 mining units were proposed.
[3]Ceased production in 1982.

TABLE 4.—Representative commodity prices in January 1981 dollars

Commodity		Price[1]
Cobalt	per lb	[2]$7.00
Copper	per lb	0.89
Gold	per tr oz	425.00
Iron	per ton	52.32
Nickel	per lb	3.45
Palladium	per tr oz	200.00
Platinum	per tr oz	475.00
Silver	per tr oz	10.00
Sulfur	per ton	117.00
Zinc	per lb	0.41

[1]Prices are 1981 average prices with adjustments to avoid extremes. All prices are from reference 11 except as indicated in footnote 2.

[2]Cobalt price (*12*) approximates the average cobalt spot prices from March 1982 to June 1983. This price from reference 12 was used to avoid the unrealistic high cobalt price that existed in January 1981.

each State and foreign country, contains the relevant fiscal parameters under which the mining firm would operate. This file includes corporate income tax, property tax, royalties, severance tax, and other taxes that pertain to the production of the commodity. These tax parameters are applied to each mineral deposit evaluated, with the assumption that every property represents a separate corporate entity. SAM also contains an additional file of economic indices to allow for continuous updating of all cost estimates to the desired study date. Upon completion of the individual cobalt property analyses, all properties included in the study were aggregated into commodity resource availability curves. The total resource availability curve is a tonnage-cost relationship that shows the total quantity of recoverable product potentially available at a specified cost. This curve is an aggregation of the total potential cobalt that could be recovered over the entire life of each operation, ordered from operations with the lowest average total cost of production to those with the highest. The curve provides a concise analysis of comparative costs associated with any given level of potential total output. Certain assumptions are inherent in the development of the curve:

1. All deposits produce at full operating capacity throughout the life of the property.
2. Each operation is able to sell all of its marketable commodities at 1981 representative prices.
3. Preproduction development of each nonproducing deposit is initiated in the same base year.

Since it is difficult to predict when deposits are going to be developed, a base year assumption is necessary. The preproduction period allows only for the minimum engineering and construction time necessary to initiate production under the proposed development plan. As a result, the additional time lags and potential costs involved in filing environmental impact statements, receiving required permits, financing, etc., are minimized.

Annual availability studies were also conducted which indicate the amount of cobalt that can be produced each year at assumed full operating capacity related to production costs.

These annual studies identify increases in availability as nonproducing deposits are assumed to go into production and show decreases as properties deplete resources.

RESERVES AND RESOURCES ESTIMATION

Resource information and other pertinent data for the 97 deposits selected for detailed evaluation have been aggregated by country and are presented in table 5. Figures 2 and 3 illustrate the locations and percentage distribution of recoverable cobalt within these countries.

Cobalt is associated with nickel in both laterite and sulfide deposits, with copper in both oxide and sulfide deposits, and with platinum-group metals in sulfide deposits; in a few cases, it is the primary commodity in sulfide or arsenide occurrences. Cobalt is a secondary commodity in approximately 97 pct of the cobalt resource.

On a regional basis, the African deposits evaluated in Zaire, Zambia, South Africa, and Zimbabwe contain the largest percentage of cobalt, 42 pct of the total evaluated resource, principally from producing properties. The circum-Pacific countries (New Caledonia, the Philippines, and Australia), account for 38 pct of the potentially recoverable cobalt; North America, 14 pct; and South America, 1 pct. New Caledonia has the largest amount of undeveloped recoverable cobalt resources, all from laterite deposits. The remaining countries account for 5 pct of potential recoverable cobalt. The 53 producing properties contribute 47 pct (1,824 million lb) of the total potentially recoverable cobalt from the evaluated deposits. Over 76 pct (1,379 million lb) of the recoverable cobalt from producing properties originates from 13 copper deposits. Thus, the majority of current cobalt production is from copper-cobalt deposits. The 13 producing nickel laterite deposits account for approximately 7 pct (267 million lb) of the total cobalt available.

The 44 nonproducing deposits contain 2,102 million lb of recoverable cobalt, 53 pct of the total potentially recoverable amount. Only 9 pct (329 million lb) of the total resource is available from four nonproducing copper sulfide and oxide deposits, whereas 36 pct (1,429 million lb) of the total potentially recoverable cobalt is from nickel laterite nonproducing deposits. Thus, the preponderance of potential cobalt resources not in production are from nickel-cobalt laterites. The distribution of cobalt resources by type and production status is shown in table 6 and illustrated by figure 4.

Potential sources of cobalt not evaluated in this study include nickel laterite deposits where cobalt is being recovered within a ferronickel product, or where cobalt grades are not available, or where cobalt is recovered from recycling operations.

Table 7 identifies 22 nickel laterite deposits not included in this study. These properties contain at least 27.8 million tons of potentially recoverable nickel; with an assumed cobalt feed grade of 0.05 pct and 27 pct overall recovery, 1,138 million lb of cobalt would be available. These sources could increase cobalt availability by 29 pct.

In addition, a significant tonnage of cobalt is potentially available from manganese seabed nodules. Nodules typically contain approximately 25 to 30 pct manganese, 1.0 to 1.5 pct nickel, 0.5 to 1.0 pct copper, and 0.25 pct cobalt (*13*). The distribution is widespread with resources located in the central east Pacific area between 0° to 20° north latitude and 120° to 180° west longitude and from 300 to 9,000 m below sea level (*14*). Assuming a nodule den-

TABLE 5.—Demonstrated in situ resources and recoverable cobalt

Country and type of deposit	Number of deposits	Primary commodity	In situ: Demonstrated resources, 10^6 tons	In situ: Primary commodity grade, pct	In situ: Cobalt grade, pct	Recoverable cobalt from producing properties, 10^6 lb	Total recoverable cobalt, 10^6 lb	Pct of total recoverable cobalt
Australia:[1]								
Sulfide	2	Nickel						
Laterite	1	... do ...	305.4	0.80	0.03	40.83	74.9	1.9
Brazil: Laterite	2	... do ...	W	1.39	.05	28.66	40.5	1.0
Canada: Sulfide	27	... do ...	811.8	1.42	.03	125.69	161.2	4.1
Finland: Sulfide	3	Copper	12.5	2.20	.26	35.05	35.05	.9
New Caledonoia: Laterite	13	Nickel	949.3	1.74	.09	10.88	1,124.45	28.7
Philippines: Laterite	3	... do ...	388.9	1.29	.10	168.40	299.27	7.6
South Africa: Sulfide	4	Platinum	1,018.6	.0003	.007	31.00	33.04	.8
United States:								
Sulfide	2	Copper	W	.93	.05	0	12.66	.3
Do	14	Nickel	3,150.4	.20	.01	0	183.81	4.7
Do	2	Cobalt	W	.44	.44	0	88.03	2.2
Laterite	4	Nickel	73.9	.84	.09	0	96.55	2.5
Zaire: Sulfide	7	Copper	612.1	4.36	.31	1,029.40-	1,315.64	33.5
Zambia: Sulfide	4	... do ...	499.7	2.92	.09	314.74	314.73	8.0
Others[2]: Various	9	Various	259.5	NAp	.07	39.45	146.11	3.8
Total	97	NAp	8,198.3	NAp	NAp	1,824.10-	3,925.94	100

NAp Not applicable. W Withheld to avoid disclosing company proprietary data; included in total.

[1]Australia tonnage and grades are combined to avoid disclosing individual proprietary information.
[2]Others include Botswana, Guatemala, India, Indonesia, Morocco, Uganda, and Zimbabwe. Primary commodities include nickel, copper, and cobalt.

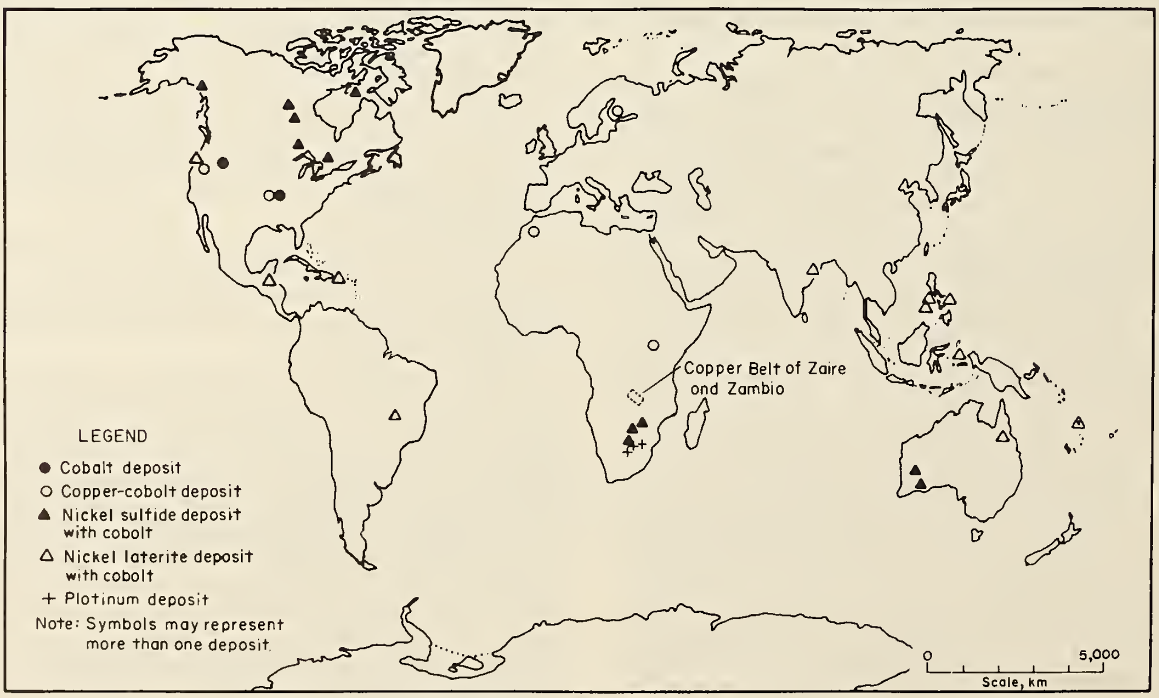


Figure 2.—Location of cobalt-bearing deposits.

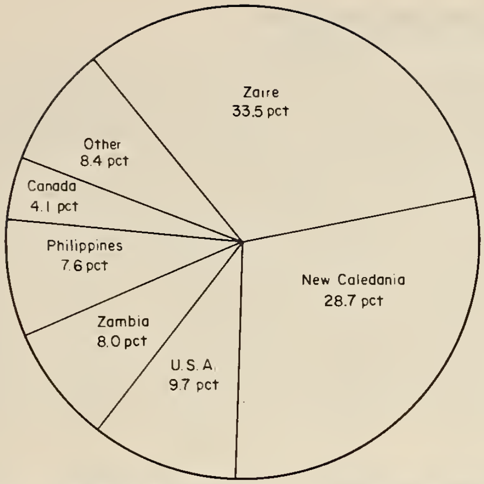


Figure 3.—Percentage breakdown of potentially recoverable cobalt by country.

TABLE 6.—Potential availability of cobalt by deposit type

Type of deposits	Number of deposits	Recoverable cobalt, 10^3 lb	Pct of total
TOTAL RECOVERABLE COBALT			
Copper-cobalt (oxide + sulfide) ...	17	1,708,000	44
Nickel-cobalt (sulfide)	47	394,300	10
Nickel-cobalt (laterite)	26	1,696,500	43
Primary and platinum-cobalt	7	127,100	3
Total	97	3,925,900	100
RECOVERABLE COBALT FROM PRODUCING DEPOSITS			
Copper-cobalt (oxide + sulfide) ...	13	1,379,200	35
Nickel-cobalt (sulfide)	23	140,900	4
Nickel-cobalt (laterite)	13	267,000	7
Primary and platinum-cobalt	4	37,000	1
Total	53	1,824,100	47
RECOVERABLE COBALT FROM NONPRODUCING DEPOSITS			
Copper-cobalt (oxide + sulfide) ...	4	328,900	9
Nickel-cobalt (sulfide)	24	253,400	6
Nickel-cobalt (laterite)	13	1,429,400	36
Primary and platinum-cobalt	3	90,100	2
Total	44	2,101,800	53

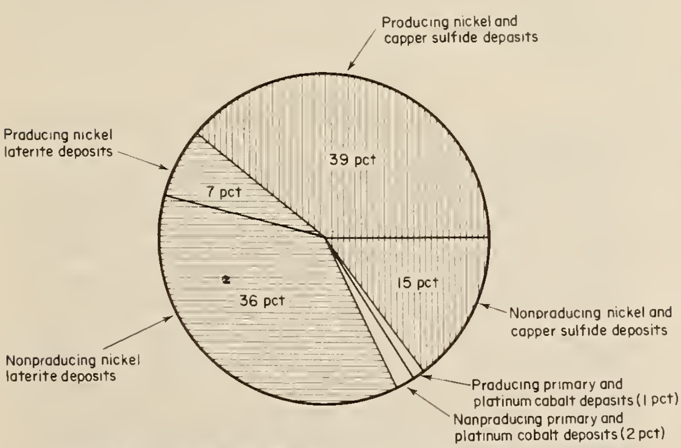


Figure 4.—Percentage breakdown of potentially available cobalt by deposit type and production status.

TABLE 7.—Nickel laterite properties excluded from cobalt study

Country and deposit name	Recoverable nickel, 10^6 ton	Assumed recoverable cobalt, 10^6 lb
Brazil:		
Barro Alto		
Jussara		
Montes Claros		
Morro do Engenho	3.7	92
Morro do Niquel		
Sao Felix do Xingu		
Sao Joas do Piaui		
Philippines:		
Borongan		
Dinagat		
Makambal		
Mount Kadig	18.1	886
Rio Tuba		
Sablayan		
Santa Cruz		
Others:[1]		
Colombia: Cerro Matoso		
Dominican Republic:		
Falcondo Bonao		
Greece:		
Euboea	6.0	160
Aghios Ioannis		
Indonesia: Pomalaa		
Malagasy Republic:		
Ambatovy and Analamy		
Valozoro		
Total	27.8	1,138

[1]Countries combined to maintain confidentiality of individual data.

sity of 11.9 kg/m², 20-pct nodule recovery rate from the ocean floor, and 30 pct moisture content, approximately 2.1 billion dry tons of nodules would be recovered. At a 50-pct recovery rate for cobalt, approximately 5.8 billion lb of cobalt could potentially be available.

The main short-term deterrents to the development of deep-sea resources are international politics regarding jurisdiction of the deposits and the massive capital investment required to develop a viable mining and beneficiation system. This resource may be a significant cobalt source in the long-range supply situation.

Several previous studies examined the world resources of cobalt (*2, 4*). Resource information from these studies was compared with the present study. Comparisons were necessary to define the scope of the study and illustrate any potential discrepancies.

A comparison of in situ resources used in this availability study with those estimated by the National Materials Advisory Board (NMAB) is presented in table 8. There is reasonable agreement for the tonnage values from Finland and Zambia.

The USBM study excluded those properties where cobalt grades were not verified or where cobalt was lost to ferronickel production. Consequently, New Caledonian properties evaluated consisted of 13 nickel laterite deposits, and tonnage data is between the high- and low-grade laterite values of the NMAB. In the case of Australia, even though similar nickel and cobalt cutoff grades are used, a considerably higher tonnage (895 versus 305.4 million tons) is reported by the NMAB. This higher figure may be the result of the inclusion of more properties in the NMAB study. For Brazil, the NMAB tonnage reflects more properties than the two included in the Bureau study.

TABLE 8.—Comparison of Bureau of Mines and National Materials Advisory Board (NMAB) estimates of in situ cobalt resources

Country	Primary commodity	Bureau of Mines: 10^6 ton	Bureau of Mines: Grade, pct Primary	Bureau of Mines: Grade, pct Cobalt	NMAB(2): 10^6 ton	NMAB(2): Grade, pct Primary	NMAB(2): Grade, pct Cobalt
Australia:							
Sulfide	Nickel				740	0.8	0.015
Laterite	... do ...	305.4	0.80	0.03	155	1.3	.1
Brazil	... do ...	W	1.39	.05	250	1.5	.13
Canada	... do ...	811.8	1.42	.03	600	1.5	.05
Finland	Copper	12.5	2.20	.26	13	3.8	.23
New Caledonia	Nickel	949.3	1.74	.09	[1]300	2.6	.09
					[2]2,500	1.4	.12
Philippines	... do ...	388.9	1.29	.10	200	1.3	.10
South Africa	Platinum	1,018.6	.0003	.007	950	NAp	.006
United States:							
Copper-sulfide	Copper	W	.93	.05	([3])	NAp	NAp
Nickel-sulfide	Nickel	3,150.4	.20	.01	[3]650	.16	.015
Nickel-laterite	... do ...	73.9	.84	.09	55	1.0	.08
Primary cobalt	Cobalt	W	.44	.44	6	1.3	.55
Missouri lead-zinc	NAp	NAp	NAp	NAp	200	NAp	.03
Zaire	Copper	612.1	4.36	.31	370	5.5	.42
Zambia	... do ...	499.7	2.92	.09	480	2.5	.14
Others[4]	Various	259.5	NAp	.07	1,057	NAp	.09
Total	NAp	8,198.3	NAp	NAp	8,526	NAp	NAp

NAp Not applicable. W Withheld to avoid disclosing company proprietary data; included in total.

[1]High-grade laterites—inferred.
[2]Low-grade laterites—inferred.
[3]Primary copper sulfides not separated from nickel sulfides.
[4]Includes Botswana, Guatemala, Indian, Indonesia, Morocco, Uganda, and Zimbabwe.

The in situ resources of the Philippines for the Bureau's evaluated deposits are larger than those of the NMAB (388.9 versus 200 million tons), owing to the inclusion of large potential resources of two mines. The large variance (612.1 versus 370 million tons) for Zaire is the result of the NMAB study excluding some lower grade properties as noted by the higher copper grade (5.5 versus 4.36 pct). In Canada, a total demonstrated resource of 811.8 million tons of nickel-cobalt sulfide from 27 properties is higher than the NMAB estimate of 600 million tons. Some of the Canadian deposits included in this study have limited development drilling information owing to Inco's policy of not disclosing drilling data and individual reserve values. Canadian companies tend to be conservative in reporting future resource estimates; thus, the individual resource values reported in this study were estimated from regional resources and are larger than the company estimates.

In the United States, 12 nickel sulfide mining units from the Duluth Gabbro Complex, Minnesota, contain more than 3 billion tons of in situ resources. NMAB may have only included deposits most likely to be developed, whereas all demonstrated resources in the district were accounted for by the Bureau in this study. Byproduct cobalt resources of Missouri lead mines were not included in this study because of the current pilot plant status of the required technology to recover and further process the cobalt-nickel concentrate.

In 1978, Wyllie conducted a world cobalt study for the Federal Republic of Germany; his reserve estimates are compared with those of this study in table 9. For New Caledonia, Zaire, and Zambia, the Bureau's resource estimates are greater than Wyllie's. Large quantities of formerly inferred tonnages have been further explored since 1978 and are reported in this study at the demonstrated level. The larger Wyllie values for Australia and the Philippines are possibly the result of Wyllie including more properties.

TABLE 9.—Comparison of Bureau of Mines and Wyllie estimates of contained cobalt resources
(Thousand tons of contained cobalt)

Country	Bureau of Mines[1]	Wyllie (3)
Australia	92	135
Brazil	29	30
Canada	244	220
Finland	33	20
New Caledonia	854	385
Philippines	389	425
South Africa	71	NAp
United States	447	NAp
Zaire	1,898	450
Zambia	450	300
Others[2]	182	700
Total	4,689	2,665

NAp Not applicable.

[1]Calculated from table 5; in situ demonstrated resources multiplied by cobalt grade.
[2]Includes Botswana, Guatemala, India, Indonesia, Morocco, Uganda, and Zimbabwe.

Wyllie did not include resources from the United States and South Africa.

The Bureau of Mines reported in a 1983 Minerals Commodity Profile (MCP), world estimates of cobalt resources that are comparable to the estimates in this study (*4*). The MCP resource estimate for Zambia includes one additional property, which was not included in our study owing to a lack of information on grade, and mining technologies at the time of the study. In Zaire, this study utilizes a conservative estimate for the reported reserves of Tenke Fungurume. For the United States, the MCP estimate includes a larger area of the Duluth Gabbro region, which was excluded in the present study owing to lack of information that could be used to relate grade and tonnage to appropriate mining and processing technologies.

GEOLOGY OF COBALT-BEARING DEPOSITS

Generally, cobalt occurs in sufficient concentration to be recovered as a byproduct in three types of deposits: (1) stratabound copper deposits located in Zaire and Zambia, (2) copper-, nickel-, and platinum-enriched magmatic sulfides such as those in the Sudbury District of Canada and the Bushveld Igneous Complex in South Africa, and (3) nickeliferous laterite deposits in such areas as New Caledonia and the Philippines. These three deposit types account for 97 pct of the potentially recoverable cobalt resources included in this study. In addition, 3 pct of the cobalt can be recovered as the primary commodity from hydrothermal deposits associated with locally concentrated veins of cobalt-rich sulfides and arsenides, such as the deposit at Bou Azzer, Morocco.

STRATABOUND COBALT-BEARING COPPER DEPOSITS

Cobalt occurrences of this type are found associated with particular copper-rich strata of sedimentary or metasedimentary rocks. This type of mineralization is found primarily in the Copper Belt of central Africa, which is about 500 km long and 30 km wide, extending from Ndola (32 km northeast of Luanshya), Zambia, to Kolwezi, Zaire (fig. 5). The copper and cobalt occur in both sulfide and oxide zones which are confined in folded and faulted strata of the Roan Supergroup of Precambrian age, which has undergone extensive folding and faulting.

Northern Copper Belt of Shaba, Zaire

The 300-km-long area, that extends from Kolwezi in the northwest to the region southeast of Lubumbashi can be divided into three groups: (1) the western group, which includes four evaluated deposits, Mutoshi-Ruwe, Kamoto underground mine, Kov open pit, and Dikuluwe-Mashamba, (2) the central group, which includes three evaluated deposits, Kambove, Tenke-Fungurume, and Kakanda-Diselle, and (3) the eastern group, which currently does not recover cobalt. The copper-cobalt ores of the Kilwezi area occur in two complex folded and faulted sedimentary horizons of the Roan.

The ore minerals of Serie des Mines in Shaba, Zaire, are chalcopyrite, bornite, linneite, and carrollite. In the oxidized zones, heterogenite and asbolite occur as secondary cobalt minerals. Both the sulfide ores and the oxides contain small amounts of selenium, uranium, gold, and platinum metals, which can be recovered as byproducts of copper-cobalt processing operations. The ore bodies, which vary in size from deposit to deposit, are 4 to 15 m thick and contain 1.8 to 5.7 pct copper and 0.13 to 0.42 pct cobalt.

The seven evaluated deposits account for approximately 612 million tons of demonstrated resources containing 19 million tons of recoverable copper and 1,316 million lb of potentially recoverable byproduct cobalt. At the 1981 annual production rate of 34 million lb of cobalt, the Zaire copper deposits contain 39 yr of production at the demonstrated resource level.

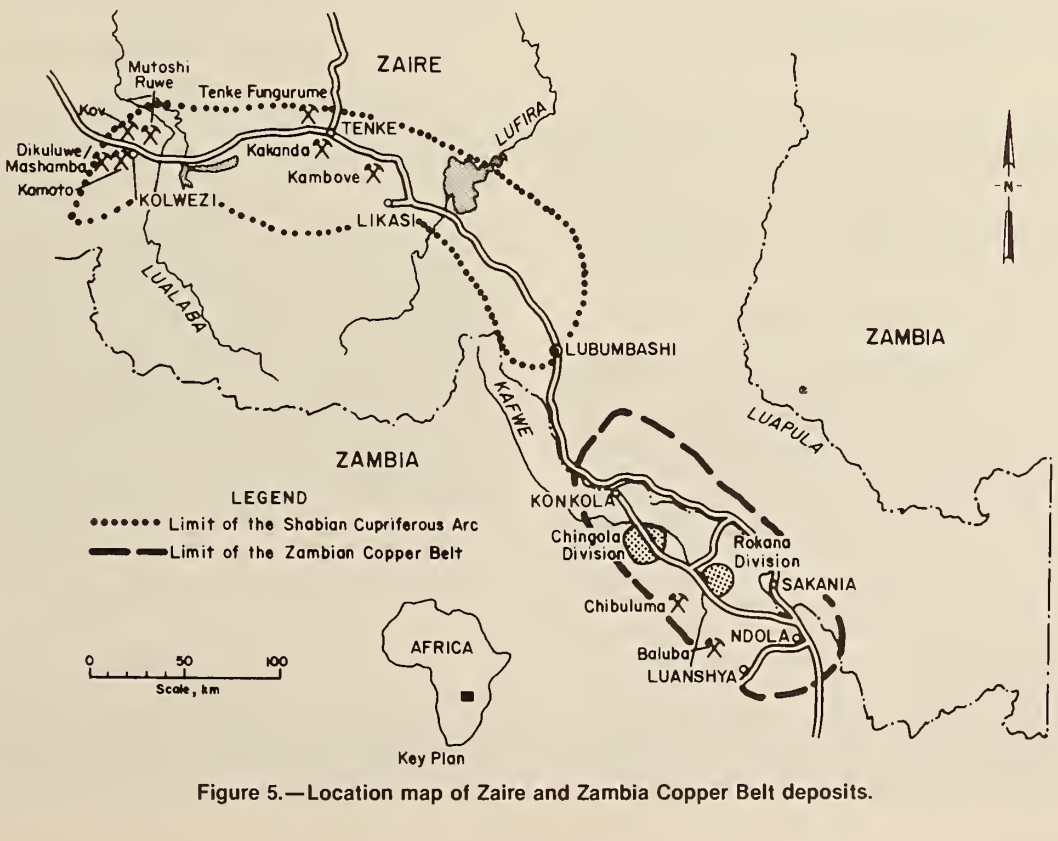


Figure 5.—Location map of Zaire and Zambia Copper Belt deposits.

Roan Copper-Cobalt Deposits of Zambia

The 200-km-long Copper Belt encompasses southeastern Zaire and extends for another 160 km into Zambia. Within the Zambian Copper Belt, cobalt mineralization is confined to the western part of the copper deposits, which consist of the Chibuluma and Baluba deposits and the Rokana and Chingola Divisions. The dominant tectonic structure in the Zambian Copper Belt is the 100-km-long Kafue anticline with a northwest-striking axis. On the southeast edge of this anticline are the major cobalt-bearing deposits of Baluba and Chibuluma.

The Chigola Division ore bodies occur along 40 km of strike in Lower Roan strata, with seven different horizons across a vertical stratigraphic column of 150 m in the sulfide mineralization. The Chingola Division consists of multiple underground and open pit mines which are referred to as one study area in this report.

The Rokana Division deposits occur in the eastern limb of the complexly folded Nkana syncline. Cobalt from the Rokana Division accounts for 38 pct of Zambian cobalt resources in this study. The Rokana Division is similar to the Chingola Division in that it consists of multiple underground and open pit mines which are evaluated as one study area.

The Zambian copper grades range from 2.4 to 4.7 pct, while the cobalt grades range from 0.05 to 0.16 pct. The mineralization, which occurs in stratabound cobalt-bearing copper deposits, consists of four sulfides—chalcocite, bornite, chalcopyrite, and carrollite—as well as oxides such as heterogenite and asbolane. The four Zambian areas studied contain 315 million lb of potentially recoverable cobalt from demonstrated resources, which represents approximately 42 yr of production at the 1981 mine capacity levels.

MAGMATIC COBALT-BEARING NICKEL SULFIDE DEPOSITS

Cobalt is also found in association with nickel-, copper-, or platinum-rich sulfide deposits in mafic or ultramafic rocks. Principal occurrences of this type included in this study are the Sudbury Complex, Ontario, Canada; the Thompson Nickel Belt District, Manitoba, Canada; the Duluth Gabbro sulfide complex of the United States; and the Merensky Reef platinum deposit of South Africa.

Sudbury, Ontario Deposits

The Sudbury Complex (fig. 6) is generally considered to be a late-stage magmatic plutonic intrusive that has undergone several stages of differentiation both before and during emplacement. The complex appears to be in the form of a southern-plunging asymmetrical funnel (*15*).

The elliptical outcrop of the complex is about 58 km long in an east-northeast direction and approximately 26 km wide. Exploration has been undertaken to depths of 3.2 km around the southern range of the basin. The southern range of this complex has been vertically upfaulted some 4.8 km relative to the northern range. Consequently, the Sudbury Complex has been studied over an apparent vertical thickness of 8.0 km.

In the Sudbury Complex, major ore minerals are typically pentlandite, pyrrhotite, and chalcopyrite; these minerals account for 95 pct of the total mineralization. Minor constituent minerals, which may be locally abundant, are cubanite, magnetite, ilmenite, and pyrite. Minerals containing platinum-group metals (e.g., sperrylite) are locally present and account for most of the byproduct platinum-group production.

Sudbury deposits can generally be divided into three categories: marginal south range deposits, marginal north range deposits, and offset deposits. Marginal deposits of the south range are generally zoned, ranging from massive ore at the footwall to disseminated ore towards the hanging wall. Ore is hosted by periodotites. The Little Stobie deposit is typical of those that occur in the south range. The mine occurs in a shallow embayment at the base of the main norite mass of the south range with major ore minerals of pyrrhotite, pentlandite, and chalcopyrite and lesser amounts of pyrite, ilmenite, and magnetite. The Little Stobie No. 1 ore body is approximately 610 m long and 30 m wide and extends from the surface to at least 800 m in depth. The Little Stobie No. 2 ore body is about 270 m long and 50 m wide and extends from a depth of 90 to 370 m (*17*).

Ores of the marginal north range deposits are associated with northeast-trending breccias, which dip southeast and vary in composition from norite to granite. The granite breccia ore contains sulfides as blebs that locally coalesce into pods or stringers as in the Levack Mine. Ore bodies occur along strike in the form of thick, blunted lenses that parallel the norite contact with estimated widths of 60 m and depths of about 1,500 m.

Offset deposits occur in a dikelike offset of sublayer norite and gabbros that extend several kilometers away from the complex into the footwall. In many cases, sulfides form lenslike pods of massive ore associated with high proportions of inclusions in offset dikes. Frood, Stobie, and Copper Cliff North deposits are examples of offset deposits. Nickel ores of the Sudbury Basin range from 0.9 to 2.5 pct nickel and 0.02 to 0.08 pct cobalt. The total in situ resource of the Sudbury Basin is about 495 million tons.

Thompson Manitoba, Belt

The Thompson Nickel Belt is located in north-central Manitoba, along the boundary between two major structural provinces of the Canadian Shield: the Churchill Province to the northwest and the Superior Province to the southeast (*18*). The Belt extends up to 208 km in a northeasterly direction. The mineralized zone of the Thompson Mine is located between two distinct markers, a skarn in the hanging wall and an iron formation in the footwall. The Thompson ore body occurs primarily as a sheetlike deposit enclosed within drag-folded units of metasedimentary rocks with the ore-bearing zone striking approximately N 30° E and dipping 65° to 75° southeast. Thickness of the ore zone ranges from less than 5 m to about 45 m at a depth up to 1,500 m. The Pipe Underground ore zone included in this study is highly joined and fractured serpentinite. Mineralization is composed of pyrrhotite and pentlandite occuring as bands and stringers of massive sulfides in serpentinite. Manitoban deposits contain 35 pct of the Canadian cobalt resource evaluated. Ore grades range from 0.8 to 2.7 pct nickel and 0.02 to 0.06 pct cobalt.

U.S. Deposits

The principal potential source of recoverable cobalt from magmatic sulfides in the United States is found in association with the Duluth Gabbro Complex in Minnesota (fig. 7). The Duluth Gabbro Complex study areas—Birch

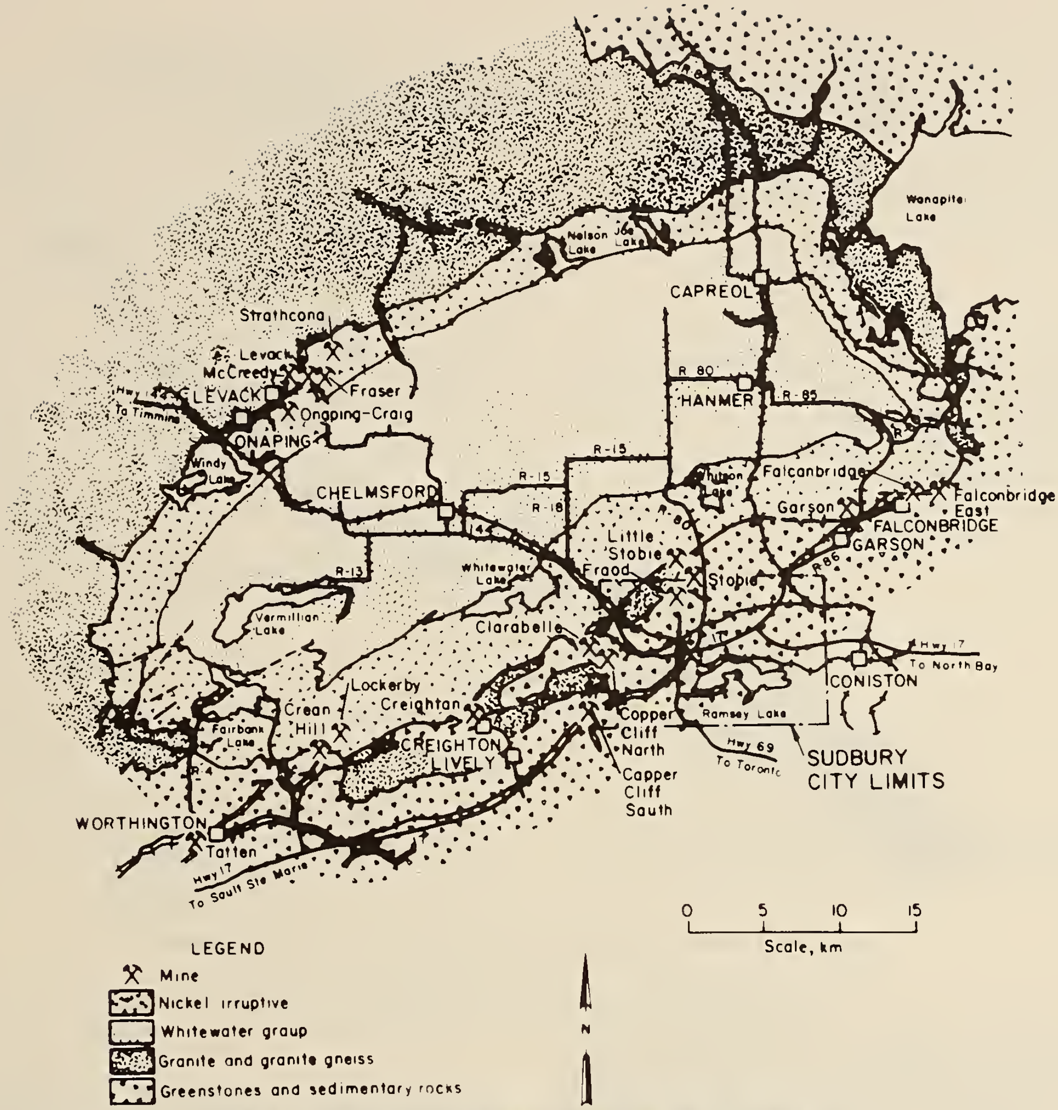


Figure 6.—Location map of Sudbury Basin deposits, Canada *(16)*.

Lake, Dunka River, Ely Spruce Underground, Spruce pit area, Partridge River, and Minnamax—occur in gabbroic igneous intrusions. Mineralization takes the form of disseminated sulfide masses, aggregates, and inclusions. Mineralization formed as a result of magmatic differentiation during the crystallization process *(18-19)*.

The principal nickel mineral is pentlandite associated with the copper minerals chalcopyrite and cubanite. Cobalt content in the deposit ranges from 0.01 to 0.02 pct. Other domestic nickel sulfide deposits included in this study are the Yakobi Island deposit, Alaska, and the Crawford Pond deposit, Maine.

South African Deposits

The Merensky Reef complex of South Africa is the principal platinum-producing region among market economy countries *(20)*. The Merensky Reef is generally a dark, coarsely crystalline pyroxenite with a chromitic basal unit. The chromitic basal band is overlain with nickel, copper, and iron sulfides which host the platinum-group metals and comprise the zone of economic importance. This zone also contains low-grade, but recoverable, cobalt (0.004 to 0.007 pct). Four separate Merensky Reef operations were analyzed for this report, three of which are currently in operation *(21)*. The producers are Rustenburg, Impala, and Western Platinum. In addition, Der Brochen, a nonproducer, was evaluated. Production is dominated by Rustenburg, which accounted for 56 pct of total South African platinum output in 1979. Impala accounted for 41 pct, and Western Platinum supplied the remaining 3 pct. All these properties are mined primarily for their platinum-group metals, with nickel and copper as major byproducts.

NICKEL LATERITE DEPOSITS

Forty-three percent of cobalt resources evaluated in this study occur in nickel laterite deposits. Nickel laterite ores are formed by the combined action of mechanical and chemical weathering *(22)*. As nickeliferous ultramafics, which contain principally the mineral olivine, decompose,

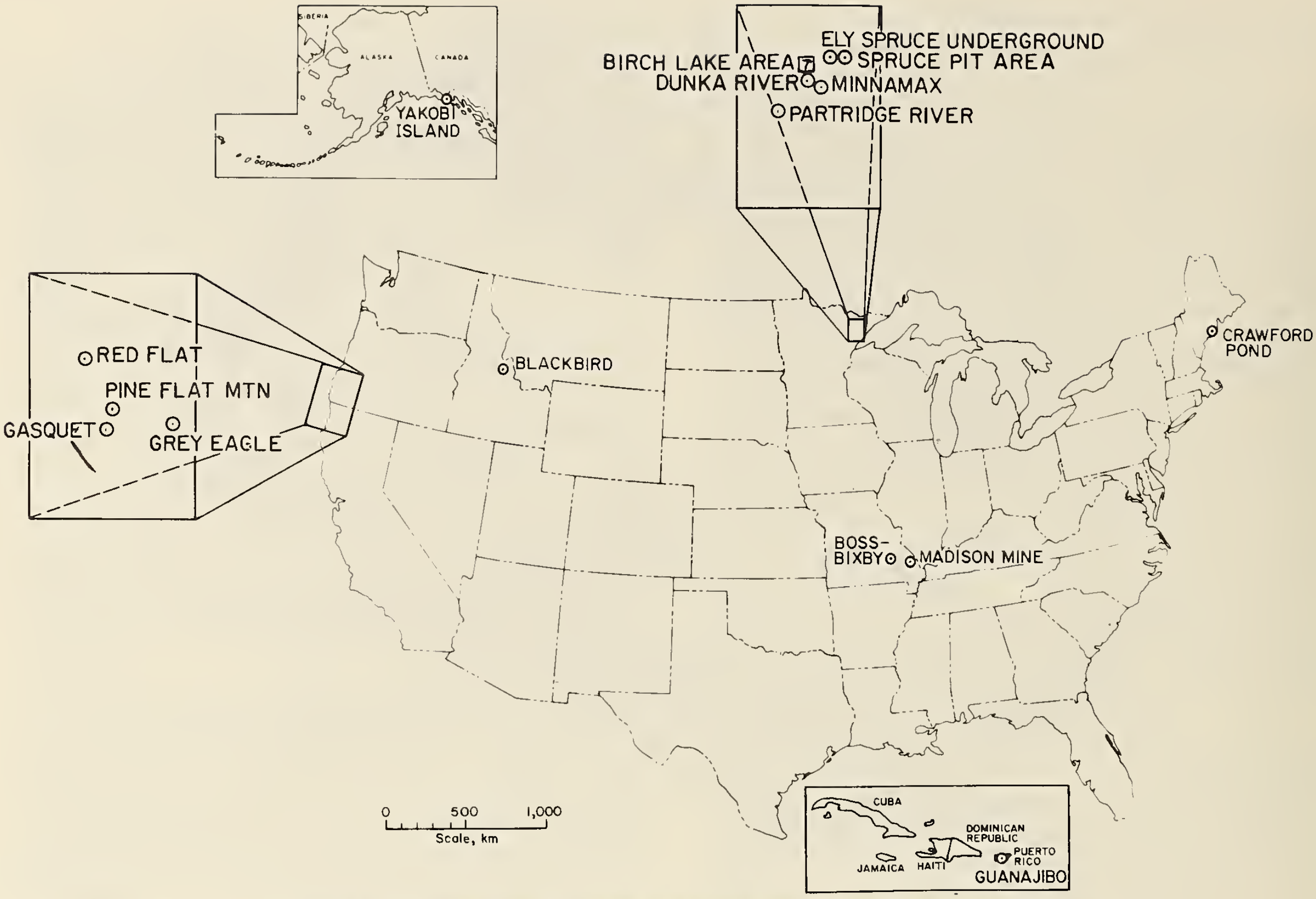


Figure 7.—Location map of cobalt-bearing deposits of the United States.

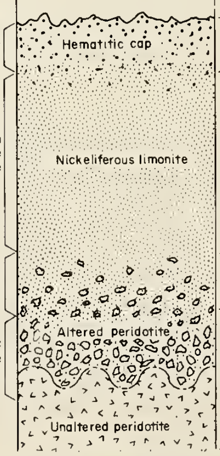
nickel and cobalt are released and mobilized into solution by the downward percolation of ground water. Nickel is redeposited at depth by precipitation. This repeated action, known as laterization, results in enriched nickel and cobalt deposits. Typically, a laterite profile contains four zones:

1. The leached zone, which is depleted of nickel.
2. The iron oxide (limonitic) zone, in which nickel is disseminated within a mixture of iron oxides.
3. The transition zone between the oxide and saprolitic (garnierite) zones.
4. The saprolitic (garnierite) zone, composed largely of hydrated magnesium silicates in which the magnesium is particularly replaced by nickel.

An idealized stratigraphic section, chemical analyses, and extractive procedures for each zone are given in figure 8. Nickel laterite deposits occur in New Caledonia, the Philippines, and the Western United States.

New Caledonia contains the largest nickel laterite resources in the study, 949 million tons from 13 evaluated deposits (fig. 9). This vast resource accounts for 29 pct (1,124 million lb) of the total potentially recoverable cobalt metal.

Deposits were formed by the weathering of Oligocene peridotites, primarily hartzburgite and dunites, which cover almost a third of New Caledonia. Although both limonitic and garnieritic laterites exist on the island, only the garnieritic laterites are mined. The zone of laterization extends to a depth of 20 m. Grade range is approximately 1.5 to 2.5 pct nickel and 0.01 to 0.13 pct cobalt.



	IDEALIZED LATERITE	APPROXIMATE ANALYSIS, pct					EXTRACTIVE PROCEDURE
		Ni	Co	Fe	Cr_2O_3	MgO	
Leached zone	Hematitic cap	<0.8	<0.1	>50	>1	<0.5	Overburden to stockpile
Iron oxide zone	Nickeliferous limonite	0.8 to 1.5	0.1 to 0.2	40 to 50	2 to 5	0.5 to 5	Hydrometallurgy
Transition zone		1.5 to 1.8	0.02 to	25 to 40	1 to	5 to 15	Hydrometallurgy or pyrometallurgy
Saprolitic zone	Altered peridotite	1.8 to 3	0.1	10 to 25	2	15 to 35	Pyrometallurgy
	Unaltered peridotite	0.25	0.01 to 0.02	5	0.2 to 1	35 to 45	Left in situ

Figure 8.—Typical nickel laterite zones.

Current operations are typically ferronickel producers or, like SLN's Doniambo operation, produce both ferronickel and matte with cobalt recovered only from the matte. For the seven properties in this area, matte smelting is proposed for 40 pct of the ore and ferronickel processing is proposed for the other 60 pct.

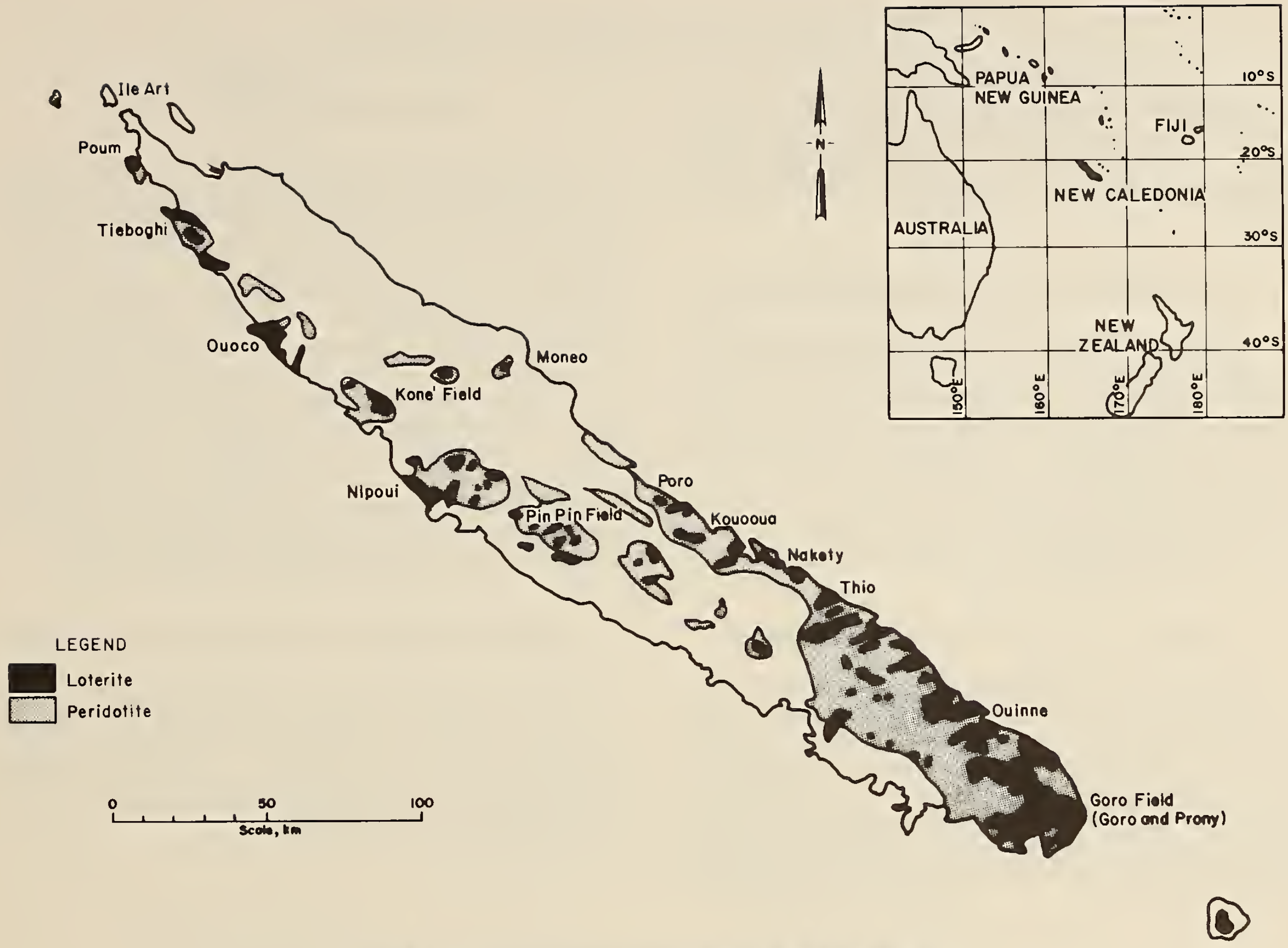


Figure 9.—Location map of New Caledonia laterite deposits.

Depending on the chemical nature of the ore, either ferronickel or nickel and cobalt can be produced. Much of the low-iron (garnieritic and/or saprolitic) ore is dried and shipped to Japan for ferronickel production, while the high-iron (limonitic) ore containing up to 0.2 pct cobalt is refined into nickel and cobalt metal. Marinduque Mining and Industrial Corp. operates a reduction roast ammonium carbonate leach refinery to recover nickel and cobalt on Nonoc Island, Philippines.

The nickel laterite deposits in the United States occur mostly in northern California and southern Oregon (fig. 7) in limonitic ore which is formed by the leaching of soils produced by the weathering of ultramafic, often serpentized, periodotite bodies. An example of this type of formation occurs near Riddle, OR, which is located on a remnant of a formerly extensive laterized plateau. The grade of domestic nickel laterite deposits, 0.75 to 0.88 pct nickel and 0.07 to 0.15 pct cobalt, is somewhat lower than that of most actively mined foreign nickel laterite deposits.

Significant nickel laterite deposits also exist in Australia, Brazil, Guatemala, India, and Indonesia. The total demonstrated laterite resource of these countries is 274 million tons. The contained potentially recoverable cobalt amounts to 176.2 million lb, 4.5 pct of the total studied amount. The dominant source for these resources is the weathering of ultramafic complexes, producing deposits 5 to 30 m thick.

PRIMARY COBALT SULFIDE AND ARSENIDE DEPOSITS

Three primary cobalt deposits, consisting of sulfide and arsenide mineralization, comprise less than 3 pct of the total cobalt resource evaluated in this study. The properties are Bou Azzer Mine in Morocco and Madison and Blackbird in the United States. At the Bou Azzer Mine, cobalt mineralization occurs in hydrothermal veins associated with Precambrian diorites and serpentinites. Ore averages 1.25 pct cobalt; the principal cobalt mineral is skutterudite.

Cobalt and nickel mineralization is present in association with lead as replacement in solution-collapse structures at the Madison deposit in southeastern Missouri (fig. 7). The principal cobalt mineral is siegenite, but cobalt is also found in chalcopyrite, sphalerite, galena, and millerite.

Cobalt also occurs in a schistose copper-cobalt sulfide zone at the Blackbird deposit in Idaho, a metasedimentary syngenetic ore body (fig. 7). Cobalt mineralization consists of chalcopyrite and cobaltite having a copper grade of 1.1 to 1.4 pct and a cobalt grade of 0.5 to 0.7 pct.

MINING OF COBALT-BEARING DEPOSITS

Included in the study are 53 operating mines; 19 utilize surface mining methods, 25 utilize underground methods, and 9 use a combination of surface and underground methods. A brief summary of mining methods is presented below.

STRATABOUND COBALT-COPPER DEPOSTS

Recovery of cobalt from the stratabound deposits is accomplished using both surface and underground mining methods. Because these deposits generally consist of sulfide and oxide ore zones, which require separate processing methods, selectivity in the method is required. Both surface and underground mining methods use drilling, blasting, loading, and hauling to recover the ore. The typical underground mining method employed in the deposits of Zambia and Zaire is sublevel open stoping.

MAGMATIC COBALT-NICKEL DEPOSITS

Magmatic cobalt-bearing sulfide ores can be recovered by underground or surface mining methods. The currently producing mines use a variety of underground methods which are specifically advantageous to particular ore bodies. Mining methods include undercut and fill, large-diameter underground blasthole mining, and vertical crater retreat. Several variations and innovations within these methods are currently being conducted in Canadian mines.

NICKEL LATERITE DEPOSITS

Laterite deposits containing cobalt are typically mined by surface methods. Owing to the unconsolidated nature of laterite ore and the relatively shallow nature of laterite deposits, mining is relatively simple, although the clearing, grubbing, and roadbuilding are often very difficult in tropical and subtropical environments. Mining of the ore entails the cutting of loading benches at specified horizontal intervals across the ore body and along the contours of the saprolite ore, which contains the highest nickel and cobalt values. Mining equipment used in this type of operation includes scrapers, small draglines, hydraulic shovels, front end loaders, backhoes, and trucks. Combinations of this equipment are used in removing the overburden and mining the ore. Because of the mineralogical zonation of the laterite deposits and the effects of certain minerals on processing, ore zones are sometimes mined selectively.

PRIMARY COBALT AND ARSENIDE DEPOSITS

In 1983, there were no mines recovering cobalt as the primary commodity. However, Bou Azzer Mine in Morocco, which closed in 1982, recovered cobalt as a primary commodity, utilizing selective underground mining methods. Primary cobalt deposits would be mined similarly to the magmatic sulfide deposits.

COBALT RECOVERY PROCESSES

Processing techniques for cobalt recovery generally vary with mineralization. A summary of processing as it relates to the mineralization is presented in the following pages. In most cases, the recovery technology is based on the recovery of a primary commodity (e.g., copper, nickel, or platinum), with cobalt often only separated in the refining stages.

COPPER COBALT-BEARING OXIDES AND SULFIDES

The oxide and sulfide ores from stratabound deposits are often directed to different circuits within each mill. The ores are then processed by crushing, grinding, and flotation. Ores containing both oxide and sulfide minerals are processed by selective flotation. In general, three types of concentrates are recovered: an oxide concentrate, a dolomitic concentrate, and a sulfide concentrate.

Smelters and refineries employ roasting, leaching, and electrowinning to recover the primary commodity and cobalt from the concentrates (*23*). The following describes processing at Zaire's Luilu refinery, the world's largest cobalt smelter-refinery (fig. 10).

Sulfide concentrate, containing 40 pct copper and 3.5 pct cobalt, is roasted to sulfate. Oxide concentrates, with 23 pct copper and 2.3 pct cobalt, and dolomitic concentrate, containing 20.7 pct copper and 1.2 pct cobalt, are mixed with the sulfate concentrate to form a concentrate for sulfuric acid leaching. Leaching and electrolytic decoppering processes recover 98 pct of the copper. The purified electrolyte solution, rich in cobalt (25 to 35 g/L), is then processed by the addition of slaked lime to precipitate cobalt hydroxide. After the cobalt hydroxide is redissolved in sulfuric acid, an electrolytic process is employed to produce 99.9-pct-pure cobalt. The cobalt metal is crushed, vacuum degassed, polished, packed, and shipped by rail to Lubumbashi for export. Similar techniques are employed at other smelters and refineries.

NICKEL COBALT-BEARING SULFIDES

The vast majority of ores from nickel cobalt-bearing sulfide deposits are concentrated by crushing, grinding, and flotation. Two concentrates are generally produced: a copper concentrate and a nickel concentrate. These concentrates are sent to a smelter and/or refinery for further processing. Processing of concentrates conducted at the smelter or refinery is exemplified by Inco's Copper Cliff smelter in Ontario, Canada, as described below (fig. 11).

Copper concentrate, which contains approximately 30 pct copper and 9 pct nickel, is dried in Inco-designed fluidized bed units. No cobalt is recovered from these copper

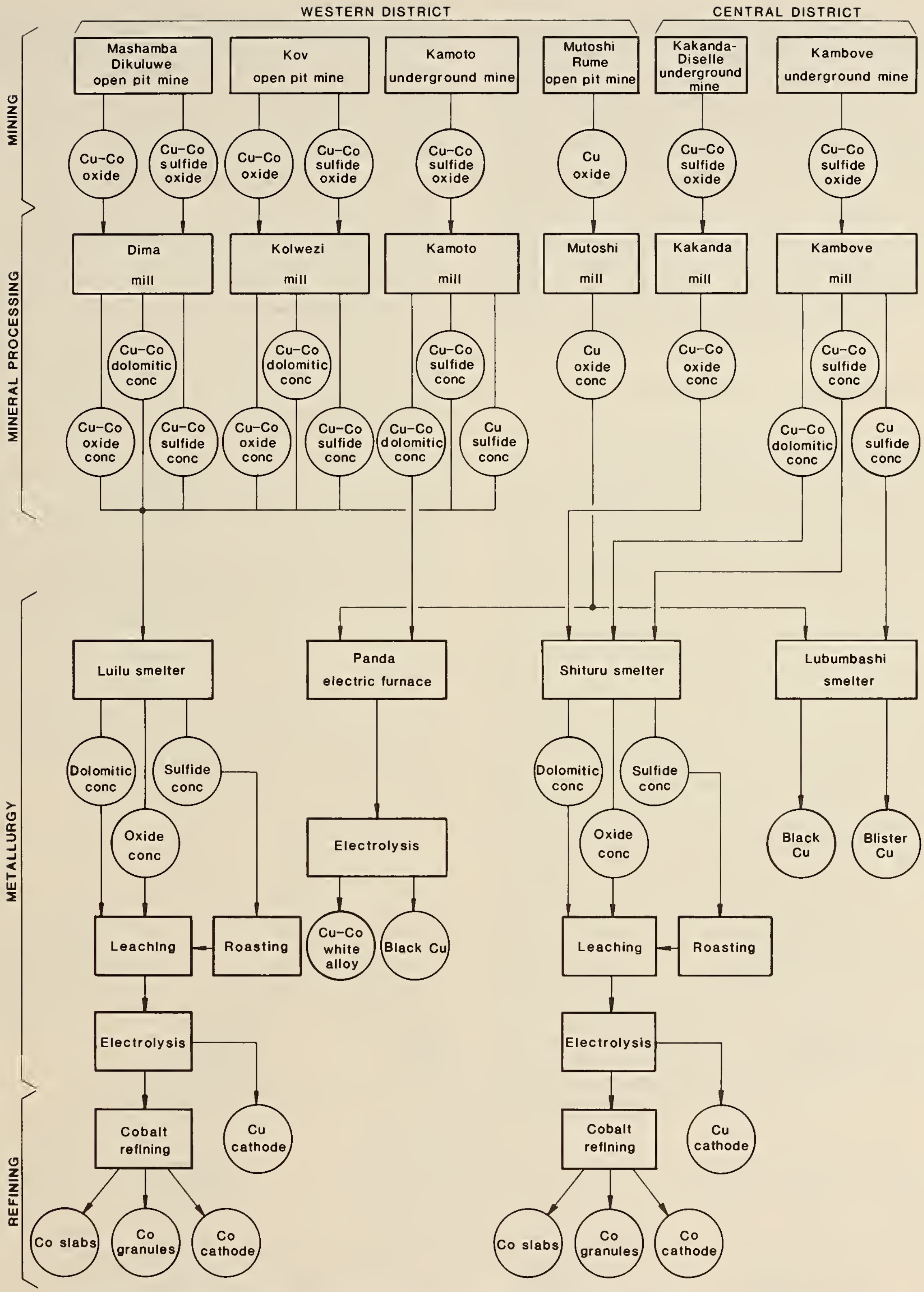


Figure 10.—Diagram of major recovery stages and key processing facilities for Zaire copper deposits.

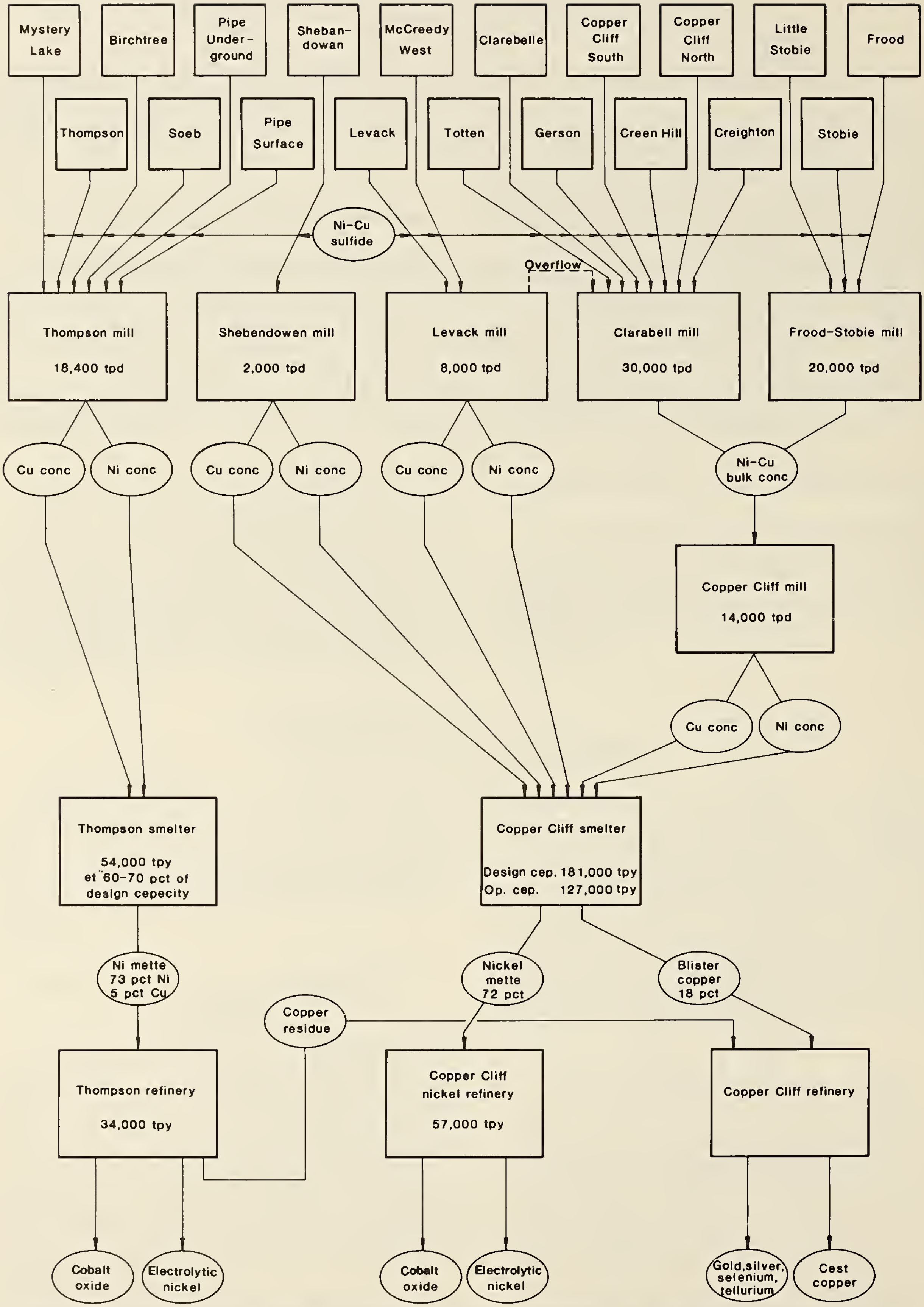


Figure 11.—Diagram of major recovery stages and key processing facilities for Inco operations at Sudbury, Canada.

concentrates. Nickel concentrate, which contains cobalt, is roasted to reduce sulfur content from 22 pct to 2.5 pct and then conveyed to reverberatory furnaces. Liquid matte is tapped from the reverberatory furnaces at a temperature of 1,150°C and further processed in Pierce-Smith converters for production of a converter matte containing approximately 50 pct nickel, 26 pct copper, 22 pct sulfur, and 2 pct cobalt. The converter matte is then cooled, crushed, and separated into magnetic and nonmagnetic portions at a matte separation plant. The magnetic portion, containing nickel, platinum-group metals, and cobalt, is sent to the Copper Cliff nickel refinery for recovery of nickel by electrolysis. Following nickel electrolysis, cobalt in the electrolyte is precipitated as cobalt hydroxide. Cobalt hydroxide is redissovled, and the solution is treated to remove iron. Cobalt is then reprecipitated before being calcined to an oxide in an electrically heated rotating kiln. The resulting cobalt oxide is leached with water to remove sulfates. The nonmagnetic portion of the matte, which contain about 1 pct nickel, is filtered and shipped to the Clydach refinery in Wales.

The Copper Cliff matte separation plant also produces nickel oxide, which is shipped to Inco's Port Colborne refinery in Ontario, Canada. The major technological steps for recovery of cobalt at the Port Colborne refinery include the casting of nickel sulfide anodes containing cobalt, the dissolution of nickel and cobalt in an electrolyte solution, and the recovery and refining of cobalt from the solution. A variation of this processing is conducted by the Falconbridge operations in Norway (fig. 12).

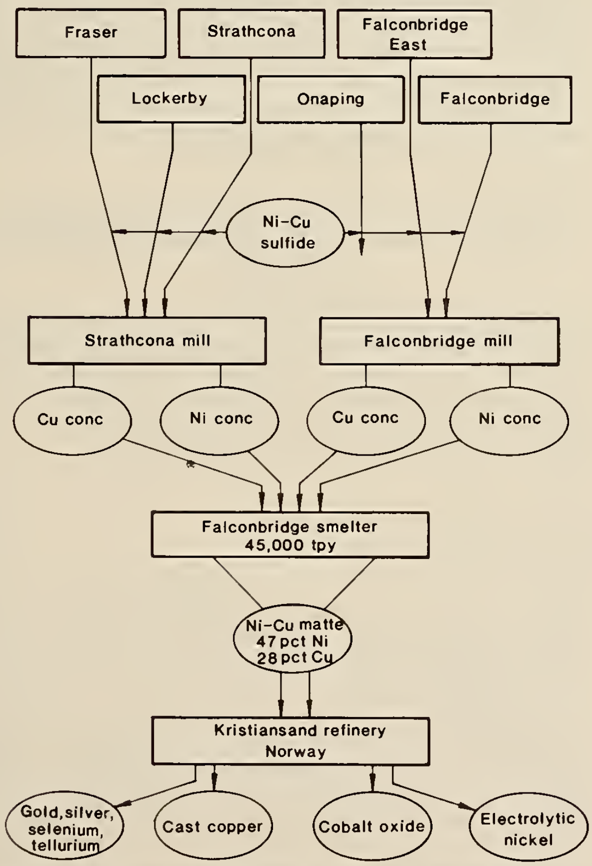


Figure 12.—Diagram of major recovery stages and key processing facilities for Falconbridge operations.

Ore from the mines is processed in the Strathcona and Falconbridge mills, which produce nickel and copper concentrates containing cobalt for the Falconbridge smelter. Crushed ore first undergoes magnetic separation. The resulting magnetic fraction is charged directly to the blast furnace or converter, while the nonmagnetic fraction is further processed to yield a nickel-copper concentrate and a pyrrhotite concentrate. The nickel-copper concentrate is pelletized and sintered before being charged to the blast furnace. The molten matte is then processed in a converter to produce the nickel-copper matte, which is shipped to Kristiansand, Norway, for final refining. The nickel and copper are separated by roasting and leaching. The oxidized matte containing the nickel and cobalt is processed to recover nickel metal through electrolysis and cobalt through precipitation and acid treatment.

NICKEL-COBALT LATERITES

In some laterite operations, preconcentration is carried out by passing the ore through rotating tommels, which break the weathered nickel silicate rock, while the unbroken, unweathered rock is discharged out the end of the tommel. The finer portion passes through the trommel as ore. In some instances, oversize from the trommel is crushed and recycled to improve recovery and to provide crushed rock for road surfaces. In the majority of cases, the laterite beneficiation consists only of crushing and drying. Laterite ores usually contain 16 to 27 pct moisture. This moisture is often reduced before leaching, smelting, or refining begins. The drying step can be a major component in the cost of nickel and cobalt recovery from a laterite deposit due to the high cost and high consumption of fuel.

Laterites pose particular problems for the recovery of nickel and cobalt owing to complex mineralogy. Pyrometallugical or hydrometallurgical processes are used. The main relationships between ore type process and cobalt recovery are shown in table 10. The four major techniques currently in commercial application include (1) matte smelting, (2) electric or blast furnace reduction to ferronickel, (3) sulfuric acid leaching at high temperature and pressure, and (4) reductive roast and/or ammonia leach.

There are major drawbacks with all four main processes currently in use. In the case of the hydrometallurgical processes, only specific feed compositions may be successfully and economically treated, while the pyrometallurgical processes are characterized by relatively high energy consumption. However, two new techniques (the new Caron process and the AMAX acid leach process) have recently been developed to improve recovery of cobalt from hydrometallurgical processes.

TABLE 10.—Nickel laterite process comparison

Process	Ore type	Cobalt recovery, pct
Pyrometallurgical:		
Smelting to matte	Blended limonite and garnierite.	20-25
Reduction to ferronickel	do	[1]0
Hydrometallurgical:		
Reduction roast ammonia leach	Limonite	40-50
Sulfuric acid leach	do	85-90

[1]No Cobalt is recovered as a separate product.

Pyrometallurgical Processes

In general, pyrometalurgy is used to treat high-grade garnieritic ores with low iron-high magnesia in the presence of suitable slag-forming minerals. Nickel recoveries of about 95 pct are typically achieved through pyrometallurgical methods. Two types of pyrometallurgical processes are used to recover nickel and sometimes cobalt from laterites: direct reduction of the laterite to a ferronickel product (containing 20 to 50 pct nickel), and smelting the laterite in the presence of sulfur in order to produce a nickel sulfide matte (containing about 75 pct nickel). In the case of ferronickel production, the cobalt is not recovered.

The recovery of cobalt in a nickel sulfide matte is possible at properties where the cobalt content is greater than 0.04 pct and the iron content is low, such as at the Falconbridge operation in Canada. Matte smelting, carried out at temperatures greater than 1,350° C, entails melting the charge in the presence of coke (for reduction) and a sulfur source. Matte smelting is used because nickel has a greater affinity for sulfur than does iron, while iron has a greater affinity for oxygen than does nickel. Thus, the product of this technique is a nickel sulfide matte, with iron present in an oxide slag. After removal of a slag layer, the iron is removed by air injection in converters. The product is an enriched matte containing nickel and cobalt, which is subsequently calcined to the oxide form, cast into an anode, and further processed by electrolysis to produce high-grade nickel and cobalt products.

Hydrometallurgical Processes

High-iron limonitic ores are processed by hydrometallurgical methods that can isolate the high iron content, thus preventing product contamination. Hydrometallurgical processes consist of variations of the reduction roast-ammonia leach process or the sulfuric acid leach process. The basic reduction roast-ammonia leach process includes drying, grinding, selective reduction in multiple-hearth roasters, ammonium carbonate leaching, separation of cobalt by solvent extraction, distillation to basic nickel carbonate, and calcining to produce nickel oxide. This process is utilized in Australia (Greenvale) and the Philippines (Marinduque). Smaller plants are starting up in India and Brazil where cobalt will be recovered. Nickel recoveries are quite low, about 60 to 65 pct, and because an additional 9 to 15 pct of nickel is recovered with cobalt as a nickel-cobalt sulfide, further refining is required to separate the nickel and cobalt (*23*).

Improvements on the reduction roast-ammonia leach process have recently been developed to increase cobalt recovery. The Universal Oil Products Co. (UOP) has developed a modification of the Caron process that uses additives in the reductive roast step to increase nickel recovery. The UOP additives, sulfur and halogen forms, make the ore more amenable to ammonia leaching.

The Bureau has modified the basic process to improve the recovery of nickel and cobalt by adding a crushed pyrite mixture before drying. This process, the USBM reduction roast ammoniacal leach (USBMRRAL), yields recoveries of about 90 pct for nickel and 85 pct for cobalt. After drying, the mixture enters the multiple-hearth roasting unit for reduction. The reduction of the laterite takes place at approximately 500° C in the presence of a heated pure carbon monoxide atmosphere. The discharge from the multiple-hearth unit is cooled, then mixed with an oxidizing ammonium hydroxide-ammonium sulfate leach solution. The leach solution dissolves the metals and some impurities contained in the reduced laterite. Cobalt and nickel are separated by solvent extration, then recovered by electrowinning (*24*).

A sulfuric acid leach process is generally applicable only to low-magnesia ores (i.e., those of the limonite zone). Under these conditions, acid consumption is minimized. The importance of this process lies in the high cobalt recoveries that can be achieved. AMAX proposes to employ this process for the New Caledonia COFREMI operation to recover nickel and cobalt from higher magnesia ores. Ore is slurried and pumped to leaching towers, where it is contacted with sulfuric acid at temperatures of 200° to 250° C under pressure of more than 500 psi. Nickel, cobalt, and magnesium are dissolved, while the iron is hydrolyzed. The solids are then separated, and nickel and cobalt are recovered from solution by hydrogen sulfide precipitation. Nickel and cobalt are subsequently refined individually by electrowining. The recoveries achieved are 90 to 95 pct for nickel and 85 to 90 pct for cobalt.

PRIMARY COBALT SULFIDE AND ARSENIDE DEPOSITS

The Bou Azzer Mine in Morocco, which recently closed operations, processed ore by gravity separation and flotation to produce a cobalt concentrate. The concentrate was then roasted, leached, and refined by electrolysis to produce cathode cobalt, reduced by roasting to produce cobalt powder, or calcined to produce cobalt oxide.

CAPITAL AND OPERATING COSTS

The wide variation in mining and processing methods used to recover cobalt is reflected in the range of capital and operating costs associated with that recovery. For each property in this study, an analysis was made of the capital and operating cost associated with the actual or proposed development of each deposit. The following sections summarize this analysis.

CAPITAL COSTS

Table 11 identifies the typical proposed capital expenditure range for deposits that are currently nonproducing. Producing deposits were not included because, in most cases, their investments have already been appreciated and new capital expenditures are limited to replacement of the facilities and expansion.

Capital investments include expenditures for property development, construction of mine and mill plant, purchase of mobile and stationary equipment, and working capital. Exploration and acquisition costs are now shown in the table; smelter and refining costs are presented where applicable. All costs are converted from currency of the country, with appropriate exchange rates, into January 1981 U.S. dollars.

The mine capital costs for development of sulfide

TABLE 11.—Typical mine and mill capital costs for undeveloped nickel deposits per annual ton ore mined (January 1981 dollars)

Mining annual capacity 10^6 tons	Ore type	Mining method	Mine capital cost	Mill capital cost	Postmill capital cost
5-14	Sulfide	Surface	$4.2-$13.7	$7.2-$10.1	(1)
.9-8.8	.....do.....	Underground	10.1-39.3	8.4-11.6	(1)
.9-3.8	Laterite	Surface	6.2-48.8	(2)	$77.8-$288.6

[1]Postmill costs in analysis were treated as a custom charge.
[2]Mill and postmill capital costs are combined. There is little beneficiation of lateritic ores.

deposits range from $4.20 to $39.30 per annual ton of mined ore capacity. The lower cost reflects open pit operations of 14,300 to 40,000 tons per day. The higher cost reflects underground mining operations ranging from 3,700 to 27,500 tons per day. In general, the costs reflect an economy of scale. The mill costs for the sulfide ores ranged from $7.20 to $11.60 per annual ton, with the higher throughput tonnages obtaining the lower costs.

For laterite deposits, the mine capital costs range from $6.20 to $48.80 per annual ton of throughput. This higher cost reflects, in most cases, the higher cost of development, clearing, etc., in the Pacific Island areas. Laterite ores are not often preconcentrated; thus, the entire mined tonnage is processed. In addition, the remoteness of many of the sites from equipment manufacturers and the necessity for large infrastructure expenditures in some undeveloped areas are reflected in the wide range of total capital cost from $77.80 to $288.60 per annual ton.

OPERATING COSTS

Approximately 97 pct of the cobalt is recovered as a byproduct from nickel and copper properties. Typical operating costs ranges by major ore type for these properties are shown in table 12. The operating cost for cobalt recovery is not separated from the operating cost for recovery of the nickel or copper, since the cobalt remains with the primary commodity through most of the processing steps. Operating costs are presented for 75 of the 90 copper and nickel properties. The 15 properties that are not included reflect unique site variations not reflective of typical operations. Table 13 shows weighted average operating cost estimates by mining type and country. Operating costs include the cost of mining, milling, smelting, and refining and all transportation up to refining. The mine and mill operating costs include labor, utilities, supplies, and the indirect costs of administration, maintenance, etc. These costs as presented do not include depreciation, interest on investments, profit, etc. All smelter and refinery costs are assumed to be on a custom charge basis.

Transportation costs, included in the "Miscellaneous other" category vary widely, depending on distance and mode. Rail and truck are common methods for transportation of concentrates to smelters and refiners within each country. Countries like the Philippines and New Caledonia depend on ocean transport for shipping of concentrates and/or partially treated ore to Japan for further processing. The transportation charges include all costs from receipt on the shipping pier to delivery at smelting facilities. The estimated transportation costs do not include tariffs or custom broker charges.

Copper Sulfide and Oxide Deposits

Included in the cost analysis are 15 copper deposits, 13 producing and 2 nonproducing properties, having total production costs ranging from $16 to $74 per ton of ore processed.

Producing mines in Finland have total operating costs of $42 to $74 per ton of processed ore. The various underground mining methods incur a mining cost of $14 to $21. Milling costs are $7 to $8 per ton of ore. Smelting and refining costs are dependent upon the cost of byproduct

TABLE 12.—Range of estimated operating costs for copper and nickel properties
(1981 dollars per ton of ore processed)

Country	Number of properties	Status[1]	Mine type[2]	Mine	Mill	Processing[3]	Miscellaneous Other[4]	Total cost	Weighted average total cost[5]
COPPER SULFIDE									
Finland	3	P	U	14-21	7-8	12-39	2-8	42-74	51
Zaire	2	P	U	< 33	<12	< 23	<5	< 68	67
Do	4	P	S	5-19	4-14	6-22	1-3	16-50	44
Zambia	4	P	S,U	12-31	6-13	9-17	.03-1.3	31-62	35
Others	2	N	S,U	<12	< 7	<12	<1.3	< 30	NAp
NICKEL SULFIDE									
Canada	14	P	U	17-37	3-12	17-63	0.12-15	56-113	77
Do	6	N	U	24-32	3-6	17-32	.04-2	54-65	58
Do	5	N,P	S	11-29	2-5	19-36	.08-2.26	38-70	40
United States	8	N	U	10-12	3-5	5-6	2-3	22-23	23
Do	5	N	S	3-10	3-5	4-10	2-3	12-26	15
Zimbabwe ...	3	P	U	13-27	2-5	23-39	.06-1	46-69	59
Others	2	N,P	S,U	26	7	36	2	67	NAp
NICKEL LATERITES									
New Caledonia	6	P	S	16-21	6	[6]138-162	25-40	187-212	195
Do	5	N	S	7	3-8	94-126	7-8	114-141	118
Others	6	N,P	S	2-13	34	10-99	0-21	52-132	NAp

NAp Not applicable. [1]P—Producing; N—Nonproducing. [2]U—Underground; S—Surface. [3]Processing cost inlcudes smelting and refining costs. [4]Includes tranportation and miscellaneous. [5]Average cost weighted by in situ resource tonnage. [6]Includes leaching cost for ferronickel.

TABLE 13.—Weighted estimated average operating costs for copper and nickel properties
(1981 dollars per ton of ore procesed)

Country	Status[1]	Mine type[2]	Mine	Mill	Processing	Miscellaneous Other	Total	Country average
COPPER SULFIDE								
Finland	P	U	16.45	7.59	21.76	4.84	50.64	50.64
Zaire	P	U	32.47	11.52	22.13	.87	66.99	50.09
Do	P	S	13.67	8.42	19.91	1.70	43.70	
Zambia	P	S,U	13.53	7.41	13.43	.34	34.71	34.71
NICKEL SULFIDE								
Canada	P	U	27.92	4.91	41.38	2.59	76.80	67.08
Do	N	U	30.12	5.07	21.90	.79	57.88	
Do	N,P	S	14.82	3.71	20.47	1.17	40.17	
United States	N	U	11.62	3.14	5.26	2.61	22.63	19.69
Do	N	S	5.20	2.85	4.90	1.95	14.90	
Zimbabwe	P	U	22.63	2.60	33.37	.87	59.47	59.47
NICKEL LATERITES								
New Caledonia	P	S	17.93	5.50	138.48	33.48	195.39	135.50
Do	N	S	6.00	7.32	98.00	7.05	118.37	
Philippines	N,P	S	3.68	5.42	87.12	14.53	110.75	110.75

[1]P—Producing; N—Nonproducing. [2]U—Underground; S—Surface.

recovery and range from $12 to $39 per ton of ore. One producer recovering gold, silver, and zinc as byproducts incurs the high processing cost of $39 per ton of ore.

In Zaire, mining costs range from $5 to $33 per ton. The open pit operations of Mutoshi Ruwe, Dikuluwe, and Kov are between $5 and $19 per ton of ore. Underground operations like Kambove Kamoto and Kakanda, employing sublevel stoping and other fill mining methods, have higher mining costs of up to $33. Milling costs range from $4 to $14 per ton of ore. Processing costs for recovery of copper and cobalt range from $6 to $23.

Total operating costs in Zambia range from $31 to $62 per ton, with a mining cost from $12 to $31 and milling cost of $6 to $13. Operations in the Rokana and Chingola divisions, which utilize many different mining methods, have mining costs of $12 to $14 per ton and milling costs of $7 to $8. The low costs are due to efficient usage of mining equipment and economy of scale in milling. Processing costs of $9 to $17 per ton are for copper and cobalt recovery and do not include any other byproducts. The two undeveloped deposits identified in table 12 as "Others" have relatively low mining and milling costs. One deposit recovers gold, silver, and zinc in addition to copper and cobalt. Total operating cost is less than $30 per ton of ore.

Comparison of the copper-cobalt operations indicates that Zambia has the lowest weighted average operating cost—about $9 per ton less than the surface operations of Zaire, and about $15 to $32 less than the predominantly underground operations of Zaire and Finland. This lower cost, however, is offset by the lower copper-cobalt grades in Zambia over Zaire, as shown in table 5.

Nickel Sulfide Deposits

There were 43 nickel sulfide deposits analyzed in this study, 22 producing and 21 nonproducing. The total operating costs of the deposits evaluated range from $12 to $113 per ton of ore processed.

In Canada, the mining costs range from $11 to $37 per ton. Underground mines using cut and fill mining methods account for the higher mine operating costs. Open pit mining costs range from $11 to $29. Milling costs for operating properties range from $2 to $12 per ton of ore. The higher end of the processing cost range reflects the cost of recovery of numerous valuable byproducts such as gold, silver, and platinum-group metals.

Undeveloped deposits in the United States, located in Alaska and Minnesota, have a total operating cost range of $12 to $26 per ton of processed ore. Mining costs range from $3 to $12. Mill operating costs are $3 to $5, and processing costs are $4 to $10 per ton of ore processed.

Producing mines in Zimbabwe have unit costs from $46 to $69 per ton of ore. Inclined cut and fill and sublevel mining methods result in mine operating costs between $13 and $27. The low milling cost of $2 to $5 is due to low wages for local employees. The highest value in the processing cost range is the result of recovering platinum at one deposit.

Comparison of the nickel sulfide operations indicates that U.S. properties have the lowest operating cost per ton. This is due to the very low grade of these deposits, which would necessitate high-capacity operations. The Canadian properties have the highest cost per ton of ore, but this will be offset by the higher grades of nickel for its properties compared with those of Zimbabwe and the United States, as shown in table 5.

Nickel Laterite Deposits

The 17 nickel laterite deposits, 9 producing and 8 undeveloped properties, have been included in this study. Total operating costs range from $52 to $212 per ton of processed ore. Laterite deposits are usually mined by surface methods. Comparing the operating costs of different laterite properties, the most important factors determining the total cost are the stripping ratios and the amount of blending and selective mining necessary to maximize the nickel and cobalt recovery.

Relatively high total operating costs with a weighted average of $135.50 for New Caledonia and $110.75 for the Philippines result from the fact that laterites are typically not concentrated prior to smelting. Lateritic ore is not amenable to upgrading by conventional beneficiation techniques; where beneficiation occurs at all, it typically includes only drying and screening. The costs are generally less than $8 except for one operation where the drying cost

at the mill site increases the mill operating cost to $34 per ton while reducing smelter and refining costs. Mine operating costs range from $2 to $21 per ton of ore. The processing costs range from $10 to $162, including costs for drying prior to smelting. The New Caledonia processing costs include separation of the ore designated for ferronickel production (60 pct) and for nickel sulfide matte production (40 pct).

Comparison of Operating Costs for Sulfide and Laterite Deposits

Copper sulfide deposits typically have an average total operating cost slightly less than those of nickel sulfide operations, excluding the low-grade U.S. properties ($50 versus $59 to $67). In addition, there is a clear difference between the operating costs associated with nickel sulfide and lateritic ores. The mine operating cost of nickel laterite ore is $2 to $21 per ton versus $3 to $37 for the nickel sulfide ores. This difference in mining costs occurs because the sulfide ores are mined almost entirely by underground methods, generally using cut and fill or other modified stoping techniques. Although some underground sulfide operations, mainly those in Canada, are now highly mechanized, the associated mine operating costs are relatively high due to the depth and high development costs for ore occurring in numerous narrow shoots and veins. Lateritic nickel deposits are mostly mined by surface cut methods.

In the case of nickel laterite deposits, the ore normally requires a large amount of energy for drying before nickel processing begins, thus causing laterite deposits to have a higher processing cost than nickel sulfide deposits. Transportation cost for the solar-dried laterite ore to processing plants in Japan is another reason for the high nickel laterite total operating cost.

POTENTIAL COBALT AVAILABILITY

The potentially recoverable cobalt resources from market economy countries are best illustrated by availability curves. These curves indicate the cost of production related to the amount of the commodity that can be recovered. The cost of production used in these analyses includes all costs through smelting and refining (f.o.b. smelter and/or refiner) and a 15-pct rate of return on invested capital. Two types of analysies were used to generate the curves illustrating cobalt availability.

In the first analysis, recoverable cobalt is related to the cobalt cost of production using 1981 representative prices for other commodities. Results of this analysis are illustrated in figure 13. This analysis indicates that the revenues derived from the production of copper, nickel, platinum, or other commodities are sufficient to totally cover the cost to recover 589 million lb of cobalt (available over the life of the properties). This cobalt can be produced at any cobalt market price if the other commodities can be sold at their 1981 representative market prices. A total of 1,330 million lb of cobalt is available at a cost of production of $7/lb cobalt. Most of this cobalt is from copper and nickel properties, with less than 3 pct from primary cobalt and platinum deposits. The cost to recover additional cobalt above 1,330 million lb increases rapidly. At a total cost of production of $25/lb cobalt, 1,953 million lb of cobalt is potentially available over the life of the properties. Thus, for the 97 deposits studied, about half of the recoverable cobalt requires a total cost of production greater than $25/lb. The highest cost tonnages typically reflect nickel laterite deposits in which the cobalt grade and recovery are low. These low-grade deposits produce correspondingly smaller amounts of cobalt, which increases the burden of the total cost per pound of recovered cobalt.

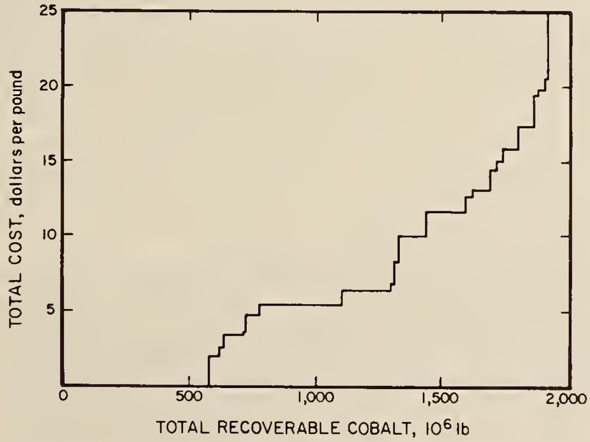


Figure 13.—Total cobalt potentially available at total production costs less than $25/lb cobalt.

The second analysis determines the cost-production relationship for the primary commodity at various cost levels using 1981 representative prices for cobalt and other byproduct commodities. Figure 14 presents the results of this analysis for properties where copper is the primary commodity. At different production costs for copper, the graph indicates the total amount of primary copper and byproduct cobalt that would be available over the life of the 17 copper-cobalt oxide and sulfide properties. For example, at a total copper production cost of $0.89/lb and a cobalt revenue based on $7/lb recovered cobalt, 22.9 million tons of copper and 1,105 million lb of byproduct cobalt would be available. At this cost of production, almost 65 pct of the total recoverable cobalt from the 17 copper properties is potentially available. At a higher total cost of production in the range of $0.89 to $1.38/lb copper, an additional 16 pct of the total recoverable cobalt from copper deposits is available. These are from 1981 copper producers that were marginal operations. The remaining 19 pct of the total recoverable cobalt is from nonproducing copper properties that have a cost of production range of $1.38 to $2.83/lb copper.

Figure 15 is a compilation of the 73 nickel deposits analyzed in the study with all byproduct prices at representative 1981 trend levels. At a nickel cost of production of $3.45/lb and a cobalt revenue based on $7/lb recovered cobalt, 8.2 million tons of nickel as a primary commodity and 190 million lb of byproduct cobalt would be potentially available. At this cost of production, only 9 pct of the total recoverable cobalt from the 73 nickel deposits is potentially

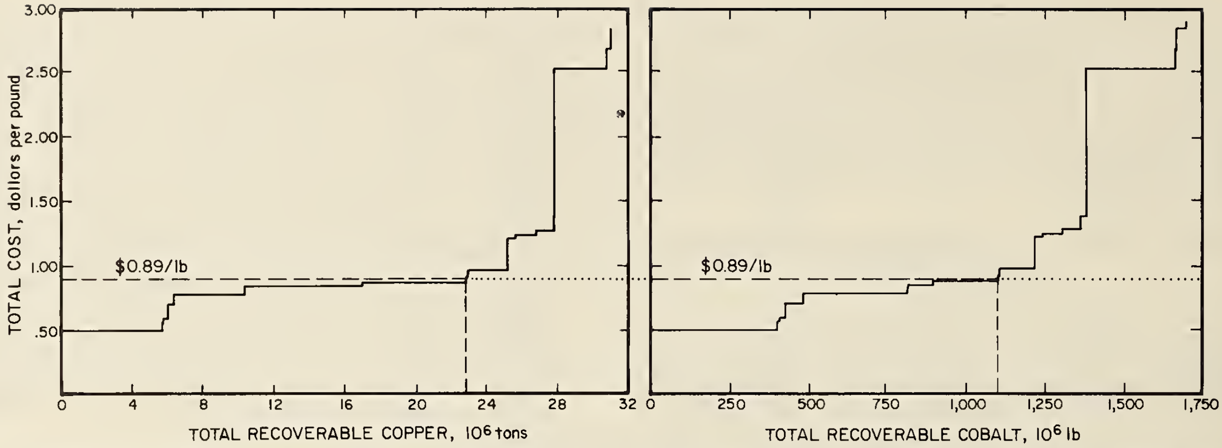


Figure 14.—Total copper and byproduct cobalt potentially available from copper-cobalt deposits at various copper total production costs.

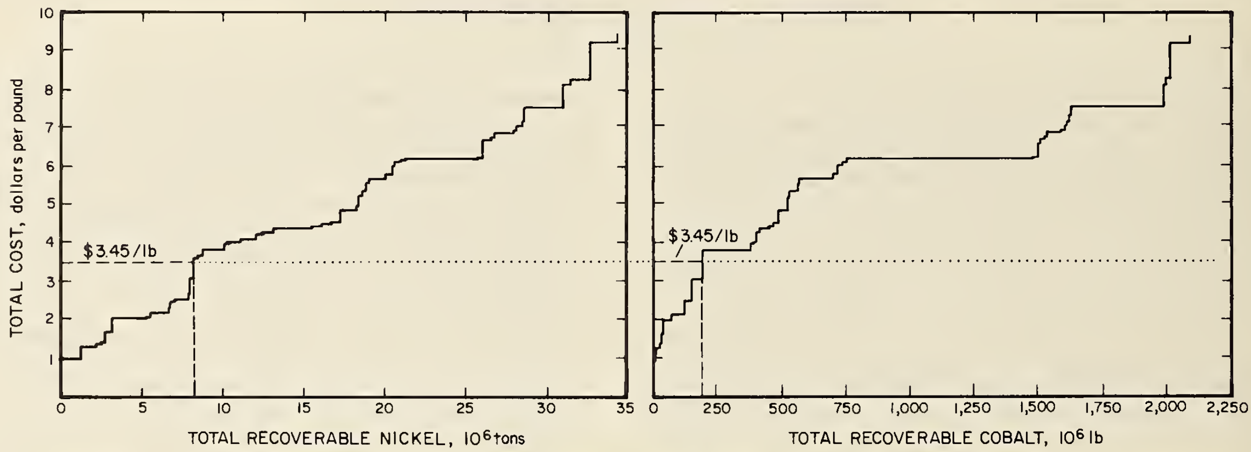


Figure 15.—Total nickel and byproduct cobalt potentially available from nickel-cobalt deposits at various nickel total production costs.

available. Over 78 pct of this available cobalt is from nickel sulfide deposits, consisting of 17 producers and 5 nonproducers. The nonproducers have not been developed principally because of sluggish nickel demand since 1981. At a higher total cost of production in the range of $3.50 to $6/lb nickel, an additional 530 million lb of byproduct cobalt is potentially available. Over 80 percent of this available cobalt is from nickel laterite deposits, 13 producers and 2 nonproducers. Thus, many of the nickel laterite producers in 1981 were marginal operations.

The remaining two-thirds of the recoverable cobalt tonnage from nickel deposits, 1,370 million pounds, can only be produced at a total cost of production of $6 to $9.21/lb nickel. Ninety percent of this cobalt is from nickel laterite deposits, all of which are nonproducers.

The four evaluated platinum properties would yield 29 million lb of cobalt at a platinum production cost of $475/tr oz and cobalt at $7/lb. The three primary cobalt properties studied provide a potential 6 million lb of cobalt at a cost of less than $7/lb cobalt.

In summary, of the 1,330 million lb of cobalt that is available, if all commodities can be produced and sold at their 1981 representative market prices, copper-cobalt properties account for 83 pct, nickel-cobalt sulfide properties for 11 pct, nickel laterite properties for 3 pct, and platinum and primary cobalt properties for less than 3 pct. The above amount is available from 27 producing deposits (7 copper, 17 nickel sulfide, 2 platinum, and 1primary) and 7 undeveloped deposits (1 copper, 5 nickel sulfide, and 1 nickel laterite). The producing mines would contribute 1,255 million lb, while the undeveloped deposits account for 75 million lb of potential cobalt production. To obtain the entire 3,925 million lb of potentially recoverable cobalt at an average total cost of $7/lb cobalt, the copper properties would require a long-term copper market price of up to $2.83/lb and the nickel properties would require a market price of up to $9.21/lb.

Cobalt availability was assessed from the major producing areas, Canada, New Caledonia, the Philippines, Zaire, and Zambia. In Canada, a total of 161 million lb of cobalt, 4.1 pct of the world total, is available from 18 producing and 9 undeveloped nickel sulfide deposits at a maximum nickel production cost of $6.17/lb (fig. 16). The producing properties account for 126 million lb of cobalt, 78 pct of Canada's resource, while the remaining 35 million lb of cobalt is from undeveloped deposits. At a cost more com-

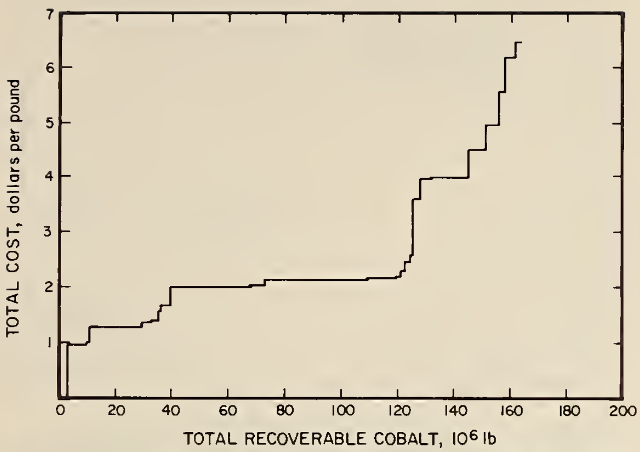


Figure 16.—Cobalt potentially available from Canadian nickel sulfide deposits at various nickel total production costs.

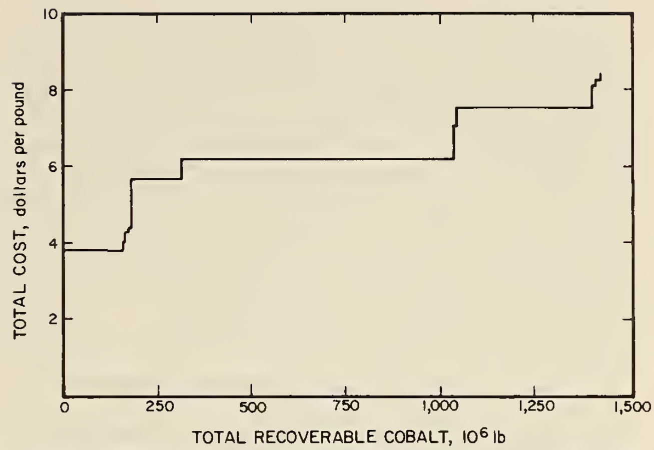


Figure 17.—Cobalt potentially available from New Caledonia and Philippines nickel laterite deposits at various nickel total production costs.

parable to the current nickel market price of $3.45/lb, about 126 million lb of cobalt can be recovered.

The laterite resources of New Caledonia and the Philippines combined account for 1,423 million lb of recoverable cobalt, 36 pct of world cobalt resources. This resource is derived from 10 producing properties and 6 undeveloped deposits. The producing properties contain 179 million lb of recoverable cobalt, 13 pct of the New Caledonia and Philippines total, while undeveloped deposits made up 87 pct (1,244 million lb) of the total. The total resource from these countries can be recovered at a nickel production cost of $8.27/lb (fig. 17). At a nickel cost of $3.45/lb, comparable to 1981 market prices, no cobalt is potentially available from these countries. Therefore, the producing mines are probably operating at less than a 15-pct rate of return on their investments.

The cobalt resources from copper oxide and sulfide properties of Zaire and Zambia are 1,630 million lb, 42 pct of the total cobalt availability. This amount is available at a copper cost of $2.52/lb (fig. 18). The evaluated cobalt resources of Zaire consist of six producing and one nonproducing properties which contain 1,315 million lb of recoverable cobalt, comprising 34 pct of the world total. Cobalt resources of Zambia consist of four producing properties totaling 315 million lb of cobalt, which is 8 pct of the world total. These countries have 1,086 million lb of cobalt available at a cost of $0.89/lb of copper; 92 pct is from Zaire.

In summary, Zambia and Zaire supply the largest

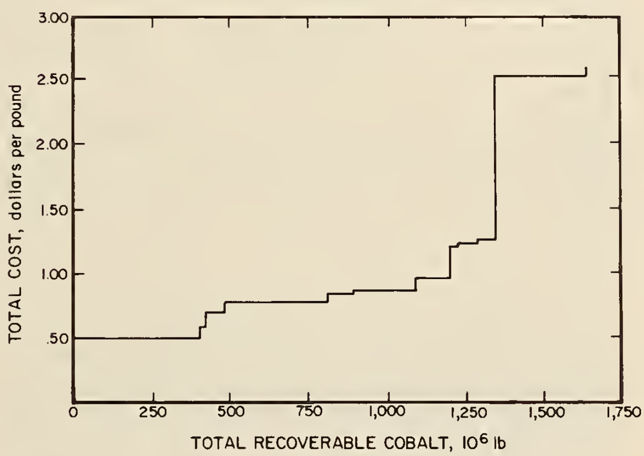


Figure 18.—Cobalt potentially available from Zaire and Zambia copper deposits at various copper total production costs.

amount of cobalt at existing market prices. A large amount of potentially available cobalt cannot be produced at a nickel cost of production less than $6.20/lb. At a nickel cost of $6.50/lb, the laterites of New Caledonia and the Philippines can potentially supply 1,036 million lb of cobalt.

ANNUAL AVAILABILITY

Availability of cobalt on an annual basis is presented for the studied operating nickel and copper properties based upon expected annual production rates. Cobalt availability from primary cobalt or platinum deposits is not discussed on an annual basis because of very small resources (only 3 pct of total). In generating these curves, cobalt price is assumed to be $7/lb, and no expansion or increase in production is proposed.

Figure 19 illustrates that for a total copper production cost of $0.89/lb, a maximum of about 44.5 million lb of cobalt is potentially available in 1984 from the producing copper-cobalt deposits. The copper-cobalt producing properties consist of 13 deposits in Finland (3), Zaire (6), and Zambia (4). The small increase in cobalt availability from 1981 to 1984 is based on proposed expansion of capacity at two properties. The availability of cobalt begins to decline in 1987, eventually reaching 29 million lb in the year 2000. This decline is based on a fixed resource base with no additional resources from exploration programs.

Annual production of cobalt from 36 producing nickel

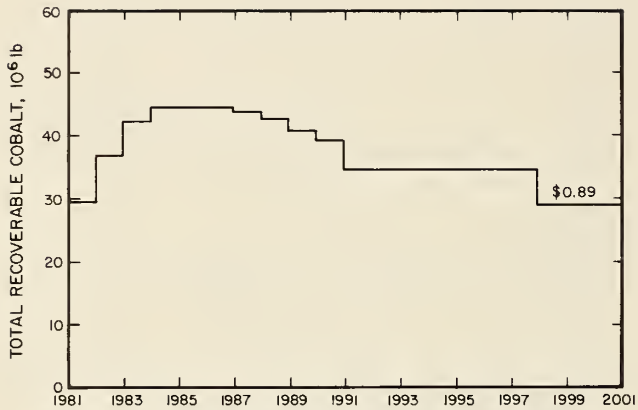


Figure 19.—Potential annual production of cobalt from producing copper deposits for $0.89/lb copper total production cost.

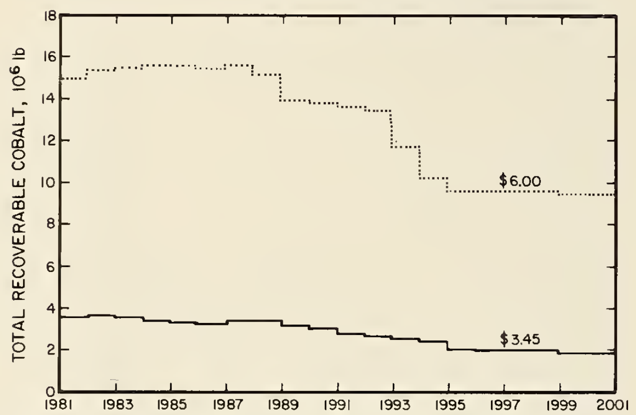


Figure 20.—Potential annual production of cobalt from producing nickel deposits for $3.45/lb and $6/lb nickel total production cost.

mines is shown in figure 20. The mines include 18 in Canada, 8 in New Caledonia, 3 in Zimbabwe, 2 each in the Philippines and Australia, and 1 each in Brazil, Guatemala, and Botswana. In 1981, these properties could potentially produce 3.6 million lb of cobalt at a nickel cost of production of $3.45/lb, all from nickel sulfide deposits. A decrease of 50 pct of the 1981 production, or 1.8 million lb of recoverable cobalt, could occur by the year 2000. For a nickel cost of $6/lb, 14.9 million lb of cobalt are potentially recoverable in 1981, 74 pct from nickel laterite deposits. At $6/lb nickel, cobalt availability gradually increases to 15.5 million lb in 1985, owing to planned expansions and some newer properties reaching their design capacity, and then decreases to 9.4 million lb in 2000. A commensurate 40-pct decrease in recoverable cobalt results between 1985 and 2000. This decline in availability for both the $3.45/lb and $6/lb cost of production levels is again due to the fixed resource estimate used in this analysis.

An annual availability analysis is also presented for the nonproducing nickel properties. As nonproducing properties are not tied to a specific startup or development schedule, it was assumed that any preproduction work would begin in a base year (*N*). These curves then illustrate the minimum startup time and maximum potential annual cobalt production from nonproducing deposits.

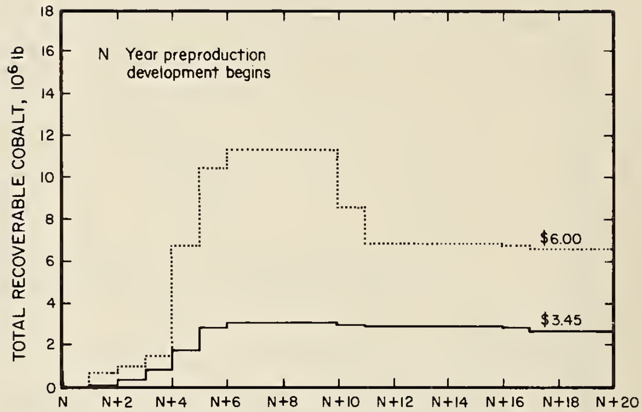


Figure 21.—Potential annual production of cobalt from nonproducing nickel deposits for $3.45/lb and $6/lb nickel total production cost.

Potential production from year N to $N+20$ is illustrated in figure 21 for 37 nonproducing nickel properties. The undeveloped nickel deposits include 18 properties from the United States, 9 from Canada, 5 from New Caledonia, and 1 each from Australia, Brazil, India, Indonesia, and the Philippines. While some deposits were in various stages of preproduction development at the time of deposit evaluation for this study and would be producing before year $N+4$, most properties are assumed to have a 4- to 10-year preproduction period, which accounts for the large surge in potential cobalt availability in year $N+4$. In year $N+4$, the potential production level for cobalt is 1.7 million lb nickel at a cost of $3.45/lb; this cobalt production is from one nickel laterite and five Canadian nickel sulfide deposits. Under the assumption that all undeveloped deposits began preproduction in year N, all properties would be producing at full capacity by year $N+9$, with a potential production level of 3.0 million lb at a total cost of production of $3.45/lb of cobalt. After year $N+9$ potential cobalt availability declines to approximately 2.6 million lb in year $N+19$.

At a nickel cost of $6/lb, 6.7 million lb of cobalt would be available in year $N+4$, with almost 80 pct from nickel laterite properties. This value increases to 11.3 million lb in year $N+6$ to $N+9$. After year $N+9$ cobalt availability steadily declines to about 6.6 million lb in year $N+20$ as the deposit resources are depleted.

An annual availability curve for nonproducing copper-cobalt deposits is not shown because of the limited number of properties (4) included in this study. At 1981 market price and assuming preproduction starts in year N, no cobalt is available from the properties until year $N+9$ when 0.5 million lb is available each year through $N+10$.

To assess the impact of the future potential availability of cobalt, a supply-demand analysis was performed (table 14). The forecast of demand for cobalt for the year 2000 is based on forecast estimates by the Bureau of Mines (*12*). Short-term estimated demands of 36 million lb for 1985 and 47 million lb for 1990 are based on data from a 1981 publication (*23*, p. 44).

At $7/lb cobalt, $3.45/lb nickel, and $0.89/lb copper, cobalt demand can be met in 1985 from producing copper and nickel mines with a surplus of 11.8 million lb. By 1990 and beyond, if we assumed that prior production has occurred at full operating capacity each year, nickel and copper producers would be unable to satisfy cobalt demand at

TABLE 14.—Comparison of annual availability of cobalt with projected demand 1985-2000
(Million pounds of recoverable cobalt)

	1985	1990	2000
Estimated demand	[1]36.0	[1]47.1	[2]67.0
Potential supply:			
Copper, producing mines	44.5	39.2	29.0
Copper, nonproducing deposits[3]	0	.5	.5
Nickel, producing mines	3.3	3.0	1.8
Nickel, nonproducing deposits[3]	1.7	3.0	2.6
Total potential supply	49.5	45.7	33.9
Surplus or shortage	13.5	– 1.4	[1]33.1

[1]Reference 23, p. 44.
[2]Reference 4, p. 12.
[3]The cobalt availability from nonproducing properties is based on initiating preproduction development in 1981 with minimum startup time.

their present production levels and therefore must rely upon copper nonproducers to satisfy the shortfall. If nonproducing nickel and copper deposits were to start preproduction development in 1981, then total cobalt availability in 1990 from these deposits would be 3.5 million lb, or slightly less than the deficiency of 3.8 million lb. In the year 2000, again with the same assumptions, the deficiency exceeds potential production by 36.3 million lb. During this year at assumed production rates and commodity prices, only 3.1 million lb of cobalt would be available from nonproducers to cover this deficiency. Beyond 1990, the obvious trend is for an ever-widening gap between cobalt demand and availability from the evaluated copper and nickel properties. This gap could be reduced by the expansion of production at properties included in this study, new discoveries, additional resource at existing mines, or increases in both the primary and byproduct cobalt market prices.

Additional cobalt could be available from producing and undeveloped nickel deposits at a higher nickel price of $6/lb. If all nickel deposits that can produce at $6/lb were to be developed, then an additional 19.1 million and 11.6 million lb of cobalt would be available in 1990 and 2000, respectively.

IMPACT OF COBALT PRICE ON COBALT AVAILABILITY

The cobalt availability analysis discussions have been related to a 1981 representative price of $7/lb for cobalt. The cobalt price, however, has increased from $3.98/lb in 1975 to $25/lb in 1980 (*8*) and declined from that high since 1981. Cobalt is recovered as a byproduct of copper and nickel; thus, the increase in cobalt price may have resulted in higher profits for the operators, even though the price of the primary commodities may have remained unchanged. Although the market price of cobalt is considerably higher than that of copper and nickel, the impact of cobalt price on the viability of an operation is limited by low cobalt grade in most ores. The effect of cobalt price on cobalt availability is illustrated in figures 22, 23, and 24 and table 15. The curves show potential cobalt availability as related to the required production cost of the primary commodity. Although the curves show cobalt availability increases that could occur at various cobalt and primary commodity cost levels, the change in the primary commodity and cobalt prices would have to be sustained over the long-term to warrant changes in production levels of cobalt or primary commodity. How long the price structure would have to be sustained is a matter unique to each producer or property owner.

COPPER SULFIDE PROPERTIES

At an average total copper production cost of $0.89/lb and a market price of $7/lb for cobalt, 1,105 million lb of cobalt could be produced from the deposits evaluated (fig. 22).[8] An increase in cobalt market price to $15/lb results in a 17-pct increase in potential cobalt availability to 1,294 million lbs, while a price increase to $20/lb results in a

[8]In these analyses, prices are real prices, whereas cost is a derived average production value generated under appropriate economic assumptions.

TABLE 15.—Effect of cobalt price on potential cobalt availability

Total cost of primary metal per lb	Cobalt at $7/lb[1]		Cobalt at $15/lb			Cobalt at $20/lb		
	Recoverable cobalt, 10^6 lb	Recoverable primary commodity, 10^6 tons	Recoverable cobalt 10^6 lb	Recoverable cobalt pct change from $7/lb	Recoverable primary commodity, 10^6 tons	Recoverable cobalt 10^6 lb	Recoverable cobalt pct change from $7/lb	Recoverable primary commodity, 10^6 tons
COPPER SULFIDE (PRIMARY METAL COPPER)								
< $0.89	1,105	22.9	1,294	+17	25.7	1,416	+28	27.9
< $1.00	1,219	25.2	1,416	+16	27.9	1,416	+16	27.9
< $1.50	1,386	27.9	1,416	+ 2	27.9	1,703	+23	30.9
NICKEL SULFIDE (PRIMARY METAL NICKEL)								
< $3.45	150	8.0	150	0	8.0	150	0	8.0
< $4.50	176	9.6	198	+12.5	10.3	198	+12.5	10.3
< $6.50	293	13.0	300	+ 2.4	13.0	317	+ 8.2	13.2
< $8.95	323	13.5	323	0	13.5	394	+21.9	15.2
NICKEL LATERITE (PRIMARY METAL NICKEL)								
< $3.45	41	0.24	226	+451.0	1.2	254	+519	1.7
< $4.50	297	7.0	297	0	7.0	297	0	7.0
< $6.50	1,212	13.1	1,220	+ .7	13.1	1,236	+2.0	13.5
< $8.20	1,684	18.2	1,684	0	18.2	1,696	+ .7	19.3

[1]Base case—cobalt market price $7/lb.

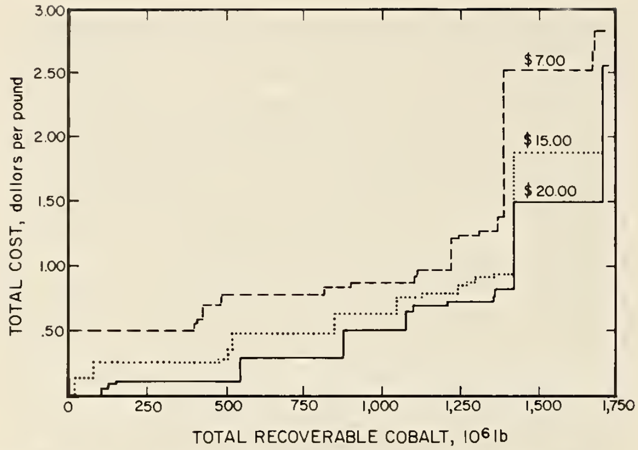


Figure 22.—Byproduct cobalt price impact on potentially available cobalt from copper sulfide deposits for various copper production costs and cobalt prices of $7/lb, $15/lb, and $20/lb.

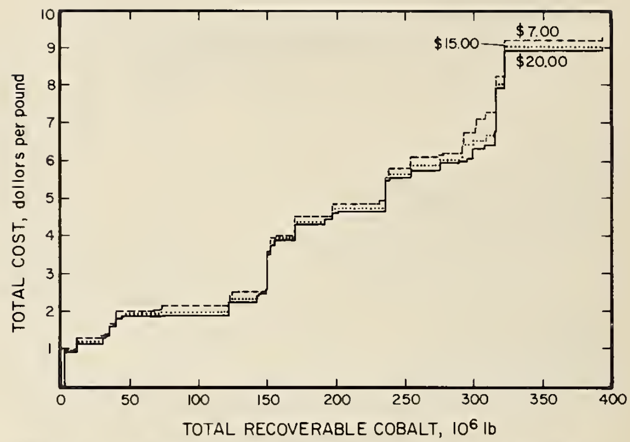


Figure 23.—Byproduct cobalt price impact on potentially available cobalt from nickel sulfide deposits for various nickel production costs and cobalt prices of $7/lb, $15/lb, and $20/lb.

28-pct increase in production to 1,416 million lb. The increase in cobalt production is due to the greater number of copper properties that can cover all costs of production with the increased price for cobalt.

At a copper production cost of $1/lb and a cobalt market price of $7/lb, the increase in potential cobalt availability is 10 pct from 1,105 million lb to 1,219 million lbs due to the greater number of copper properties that can produce cobalt and cover all costs of production at $1/lb copper. At $1/lb copper production cost and $15/lb cobalt price, a 16-pct increase in cobalt availability occurs. The amount of cobalt and copper available at $1/lb copper and $15/lb cobalt is the same as that at $0.89/lb copper and $20/lb cobalt. This illustrates the less sensitive nature of cobalt as a byproduct to the total cost of production. The same cobalt availability is achieved with a $5/lb increase of cobalt price to $20/lb as with an $0.11/lb increase in copper price from $0.89 to $1. There is no additional change that occurs in either cobalt or copper availability when the cobalt market price is increased from $15/lb to $20/lb and copper is at $1/lb.

When the cost of copper production is increased to $1.50/lb and the cobalt price remains at $7/lb, cobalt availability increases to 1,386 million lb. The 69-pct increase from the base copper production cost to $1.50/lb results in a larger potential availability of cobalt than does increasing the cobalt price by 114 pct to $15/lb with copper production cost at $0.89/lb. At the $1.50/lb copper production cost level, a 2-pct increase in cobalt potential production, from 1,386 to 1,416 million lb, occurs when the cobalt market price is increased from $7/lb to $15/lb. At $20/lb cobalt, 1,703 million lb of cobalt is potentially recoverable.

NICKEL SULFIDE PROPERTIES

At an average total production cost of $3.45/lb for nickel and a market price of $7/lb for cobalt, 150 million lb of cobalt is potentially available from nickel sulfide deposits (fig. 23). An increase in market price of cobalt to $15/lb and $20/lb causes no change in availability of cobalt. The increase in the potential revenue of cobalt is not sufficient to reduce the total cost of production of any of the higher cost properties to the $3.45/lb nickel level. This is due to the low cobalt recovery and grades of many of the nickel properties, which are not as sensitive to higher cobalt prices.

When the cost of nickel production is increased to $4.50/lb, cobalt production increases to 176 million lb for the $7/lb cobalt price. When the cobalt price is $15/lb, the potential cobalt availability is increased by 12.5 pct to 198 million lb. A cobalt price increase to $20/lb would bring in no new cobalt production. Some higher cost sulfide operations are almost viable at a nickel production cost of $4.50/lb and are sensitive to cobalt price changes, as can be noted by the slight increase in nickel and/or cobalt availability at this level as the cobalt price increases. At an average total production cost for nickel of $6.50/lb, cobalt availability is insensitive to cobalt price. All cobalt from nickel sulfide properties is potentially available at $20/lb cobalt and $8.95/lb nickel.

NICKEL LATERITE PROPERTIES

Nickel laterite deposits typically have higher production costs than nickel or copper sulfide deposits (fig. 24).

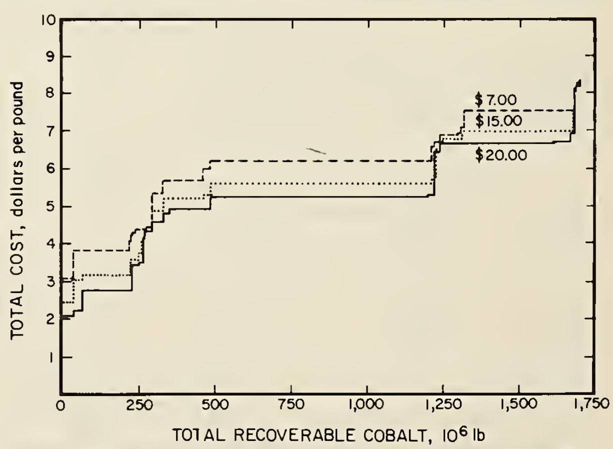


Figure 24.—Byproduct cobalt price impact on potentially available cobalt from nickel laterite deposits for various nickel production costs and cobalt prices of $7/lb, $15/lb, and $20/lb.

The vast majority of nickel laterite deposits cannot go into production at a nickel price of less than \$6.50/lb. The small number of nickel laterite properties that are economically viable at \$3.45/lb are very sensitive to cobalt price. At the market price of \$7/lb cobalt, potential production of cobalt is 41 million lb. When cobalt price is increased to \$15/lb, an increase of 451 pct to 226 million lb of available cobalt occurs. At a cobalt price of \$20/lb, cobalt availability is increased 522 pct to 255 million lb.

The fourfold and fivefold increases in cobalt availability as the cobalt price changes from \$7/lb to \$15/lb and \$20/lb illustrate the sensitivity of nickel laterite operations to cobalt price changes when the primary commodity of nickel remains constant at \$3.45/lb. Most of the properties that can produce at less than \$6.50/lb nickel are available at \$7/lb cobalt and \$4.50/lb nickel, and thus further increases in cobalt price do not increase availability. Thus, there is no change in availability of cobalt as the cobalt price increases from \$7 to \$20 per pound.

At average total production cost levels of \$6.50/lb and \$8.20/lb for nickel, cobalt availability is not as sensitive to cobalt price variations. The insensitivity of nickel laterite deposits to higher cobalt prices is due to low cobalt recovery and grade. All cobalt is potentially available at \$20/lb cobalt and \$8.20/lb nickel from nickel laterite deposits.

IMPACT OF ENERGY COSTS AND CAPITAL INVESTMENTS ON COBALT AVAILABILITY

Currently, in most countries energy costs and capital investment requirements are increasing. These increases, without a comparable increase in the market price of the recovered commodities, will reduce the availability of economic mineral resources. Sensitivity studies were conducted to indicate the impact of each of these cost variables on the availability of cobalt and the associated primary commodities of copper and nickel.

IMPACT OF ENERGY COSTS

The 1970-80 rise in energy costs significantly affected nickel and copper production and thus cobalt availability. From 1977 to 1979, fuel oil costs rose as much as 52 pct (*25*, p. 81). When the increased energy costs per pound of nickel were compared to the price change from 1972 to 1977, a significant impact was noted. In the case of nickel sulfide ores, the energy cost increase accounted for a 36-pct increase in the production cost. For nickel laterite ores, the energy cost increase accounted for a production cost increase of 73 to 138 pct over this time frame. Most nickel sulfide deposits are located in countries where low-cost coal and hydroelectric power are readily available. Countries having laterite deposits often rely largely on imported fuel oil for energy requirements. A number of laterite producers, including the Marinduque Mine in the Philippines and Greenvale in Australia, are considering coal conversion projects, but whether the potential savings will fully justify the additional capital costs has yet to be determined. Energy costs account for 15 to 20 pct of total operating costs for nickel sulfide ores and 40 to 60 pct for nickel laterite ores (*26*).

Table 16 shows the effect of a long-term increase in energy costs on the availability of cobalt from the copper and nickel properties when energy costs were increased 20, 50, and 75.

For copper sulfide deposits, an average total cost of \$0.89/lb copper was selected to measure the impact of energy cost increases. As table 16 indicates, copper sulfide operations are insensitive to energy cost increases with decreasing amounts of recoverable cobalt ranging from 1 pct at a 20-pct increase in energy costs to 8.5 pct at a 75-pct increase in energy costs. Each 10-pct increase in energy costs tends to increase the total production cost an average of \$0.02/lb copper. This is due to the low-cost nature of many of the copper-cobalt properties, which can absorb the increased energy costs and still have a total production cost of less than \$0.89/lb copper.

Many nickel sulfide mines operate at a total production cost of less than \$2.50/lb nickel; therefore, a nickel average total cost of \$2.50/lb was used to illustrate the impact of energy cost. At energy cost increases of 20, 50, and 75 pct, only a 6-pct decrease in cobalt availability occurs, indicating that the energy impact on nickel sulfide is minimal. Each 10-pct increase in energy cost tends to increase total

TABLE 16.—Impact of energy cost on cobalt availability from nickel and copper deposits

Pct energy cost increase over base case	Copper sulfide deposits[1]		Nickel sulfide deposits[2]		Nickel laterite deposits[3]	
	Recoverable cobalt 10^6 lb	Change from base, pct	Recoverable cobalt, 10^6 lb	Change from base, pct	Recoverable cobalt, 10^6 lb	Change from base pct
(Base case)	1,105	NAp	130	NAp	1,212	NAp
20	1,093	−1	123	−5	486	−60
50	1,011	−8.5	122	−6	356	−71
75	1,011	−8.5	122	−6	297	−75

NAp Not Applicable.

[1]Average total production cost of \$0.89/lb of copper.
[2]Average total production cost of \$2.50/lb of nickel.
[3]Average total production cost of \$6.50/lb of nickel.

TABLE 17.—Impact of capital investment on cobalt availability from undeveloped properties[1]

Average total cost of nickel per lb	Base case: recoverable cobalt, 10^6 lb	25-pct increase in capital investment: Recoverable cobalt, 10^6 lb	25-pct increase in capital investment: Change from base, pct	50-pct increase in capital investment: Recoveragle cobalt, 10^6 lb	50-pct increase in capital investment: Change from base, pct
Less than $3.45	68(6)	68(6)	0	49(5)	−28
Less than $4.50	117(10)	84(8)	−28	84(8)	−28
Less than $6.50	1,106 (20)	325(16)	−71	306(14)	−72

[1]Numbers in parentheses represent the number of properties included in the average total cost range.

cost by an average of $0.03/lb nickel. Again the low-cost nature of many of the nickel sulfide properties allows them to absorb the additional energy cost and still have a total cost of production of less than $2.50/lb.

Nickel laterite operations are presented at $6.50/lb nickel in order to better reflect the total production costs and sensitivity to energy of these operations. Nickel laterites are very sensitive to energy cost changes; an increase of 20 pct in energy costs will decrease cobalt availability by 60 pct. When the cost of energy is increased 75 pct, a decrease of 75 pct occurs in cobalt availability. Each 10-pct increase in energy cost tends to increase the total cost by an average of $0.16/lb nickel. Since laterite ores generally contain about 25 pct moisture, energy consumption for drying prior to smelting results in high cost sensitivity. Nickel laterites account for 84 pct of potentially recoverable cobalt from undeveloped deposits; consequently, energy increases impact directly on cobalt availability from these sources.

IMPACT OF CAPITAL COST

The impact on the availability of cobalt due to increased capital investments of 25 and 50 pct is shown in table 17. Only undeveloped deposits are selected for this analysis because investments for most of the producing deposits have already been depreciated and new capital expenditures are limited to replacement of the facilities and expansion. Lack of a large number of properties would produce a correspondingly narrow analysis for the copper properties; thus, only undeveloped nickel sulfide and laterite properties have been analyzed.

Without any increase in capital costs, the base case reveals the following potential cobalt availability from the undeveloped nickel deposits: 68 million lb from 6 properties at less than $3.45/lb nickel, 117 million lb from 10 properties at less than $4.50/lb, 1,106 million lb from 20 properties at less than $6.50/lb. When capital costs are increased 25 pct, no change occurs at a cost of production less than $3.45/lb nickel. This is due to the fact that these properties have a cost of production closer to $2.50/lb and thus were able to absorb the capital cost increase and remain under $3.45. At a 50-pct increase in capital cost, one of the properties can no longer produce at $3.45/lb nickel.

For properties able to produce at $4.50/lb nickel, an increase of 25 pct capital cost will eliminate two properties and decrease available cobalt by 28 pct; no further change occurs with a 50-pct capital cost increase.

The drastic decrease in cobalt availability at less than $6.50/lb nickel with capital cost increase from 25 to 50 pct reflects that many of these properties have costs of production close to $6.50 and the capital cost increase is sufficient to increase the costs of production above the less-than-$6.50/lb range.

CONCLUSIONS

Cobalt availability from mineral sources was analyzed by completing economic evaluations of selected mineral deposits that produce cobalt as a primary product or byproduct. The average cost of production, including a 15-pct DCFROR for each deposit, was estimated. The properties were grouped by deposit type, country, and production status.

The evaluated deposits have a total potentially recoverable cobalt resource of 3,926 million lb at the demonstrated level: 33.5 pct from Zaire, 28.7 pct from New Caledonia, 9.7 pct from the United States, 8.0 pct from Zambia, 7.6 pct from the Philippines, 4.1 pct from Canada, and 8.4 pct from other countries.

Cobalt recovery is dependent not only on its market price, but also on the market price of the primary commodity with which it is associated. A change in the primary commodity price impacts the availability of cobalt. At 1981 trend prices, a total of 1,330 million lb of cobalt is recoverable: 83 pct from copper deposits, 11 pct from nickel sulfide deposits, 3 pct from nickel laterite deposits, 2 pct from platinum deposits, and 1 pct from primary cobalt deposits. The above amount is available from 27 producing deposits (7 copper, 17 nickel, 2 platinum, and 1 primary) and 7 undeveloped deposits (1 copper and 6 nickel). The producing mines would contribute 1,255 million lb, while the undeveloped deposits would account for 75 million lb of total potential cobalt production. To obtain the entire 3,926 million lb of potentially recoverable cobalt at an average total cost of $7/lb cobalt, the copper properties would require a long-term copper market price of $2.83/lb and the nickel properties would require a market price of $9.21/lb.

Based upon 1981 market prices and existing or expected increases in annual capacities, the 24 producing nickel and copper properties that can cover their total cost of production, including a 15-pct DCFROR, can meet forecasted cobalt demand for only the next decade. The poten-

tial capacity levels of these properties are 47.8 million lb in 1985 and 42.2 million lb in 1990. By 1990 and beyond, forecasted demand will exceed annual capacity unless non-producing properties start production, current producers expand capacity, or marginal producers can continue to operate over the long term.

At 1981 market prices, seven currently undeveloped deposits could cover their total cost of production; six of these are nickel deposits that have not been developed due to sluggish nickel demand, and one is a copper deposit with limited resources. These properties account for a potential annual capacity of 1.7 million lb of cobalt in 1985 and 3.5 million lb in 1990. These seven undeveloped deposits, principally in North America, would be the first expected new producers if demand increased.

For the studied deposits, 25 producing properties are not able to cover all costs of production at 1981 market prices. Six of these properties are copper producers whose costs of production range from \$0.90 to \$1.39/lb copper; 19 are nickel properties with costs of production ranging from \$3.50 to \$6.82/lb nickel. These properties, which could account for an annual capacity of 23.8 million lb of cobalt in 1985, will only produce for the long term if market prices of the recovered commodities increase or if Government policies or subsidies or company policies allow continued production.

Nineteen undeveloped nickel sulfide deposits have total production costs ranging from \$3.59 to \$9.21/lb nickel. However, 42.6 pct of the cobalt resources from these properties can be produced at less than \$6/lb nickel with an annual capacity of 7.4 million lb in 4 yr after preproduction is initiated. These deposits are in North America and could provide a future cobalt source if nickel price and demand increase.

Two undeveloped nickel laterite deposits have total production costs between \$3.50 and \$6/lb nickel, and their contribution with 4-yr preproduction could be 4.2 million lb of cobalt. Finally, of the studied properties, 13 copper and nickel laterite nonproducing deposits have such a large production cost that their availability for production in the near future seem unlikely. Three of these deposits are copper-cobalt properties, with a total cost of production of over \$2.50/lb copper. Ten are nickel laterite deposits with a total cost of production of over \$6/lb nickel, principally from Pacific Basin deposits. Their contribution with 4 yr of preproduction could be 19 million lb of cobalt at proposed capacities.

This study has further indicated the loss of cobalt to ferronickel production from 22 nickel properties as 1,138 million lb. This cobalt will only be available if technology and market conditions change in favor of matte production.

The nickel laterite properies proved to be the most sensitive with respect to energy cost change. An increase in energy costs of 20 pct would decrease cobalt availability by 60 pct from nickel laterites. Capital investment cost increases can significantly affect the availability of nickel and cobalt; an increase of 25 pct reduces cobalt availability from the undeveloped nickel deposits 71 pct at \$6.50/lb nickel.

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APPENDIX.—Properties investigated but not included in study[1]

Country and property name	Status[2]	Type of operation[3]	Owner
		NICKEL-COBALT PROPERTIES	
Australia:			
Agnew	P	U	Agnew Mining Co.
Ora Banda	P	S	Western Mining Corp.
Sherlock Bay	N	U	Australian Inland Exploration Ltd.
Wannaway	N	U	Metals Exploration Ltd.
Windarra	N	U	Western Mining—Shell Australia.
Wingellina	N	S	Texas Gulf.
Brazil:			
Barro Alto	N	S	Baminco-Mineracao, Siderurg.
Jussara	N	S	Companhia Minerada Montita.
Montes Claros	N	S	Vatorantin Financial Group.
Morro do Engenho	N	S	Companhia Do Pesquiso Do.
Sao Felix do Xingu	N	S	Mineracao Do Sul.
Sao Joaos do Piaui	N	S	Rio Doce Geologica E Miner.
Canada:			
Bowden Lake	N	U	Falconbridge and others.
Dumont Nickel	N	S	Boliden AB and Timiskamig.
Expo Ungava	N	S	Expo Ungava Mines Ltd.
Moak	N	S	Inco.
Raglan Nickel Deposit	N	U	Falconbridge.
Texmont	N	U	New Texmont Exploration Ltd.
Colombia: Cerro Matoso	N	S	Econiquel-Billiton-Hanna.
Dominican Republic: Falcondo Bonao	P	S	Falconbridge.
Finland:			
Hitura	P	S	Outokumpu Oy.
Kotalahti	P	U	Do.
Greece:			
Euboea	P	S	Larco.
Ioannis	P	U	Do.
Indonesia:			
Pomalaa	P	S	Indonesian Government.
Soroako	P	S	P. T. Inco.
Philippines:			
Acoje	P	S	Acoje Mining Co.
Borongan	N	S	G. Y. Ornopia and Associate.
Dinagat	N	S	Marinduque Mining Corp.
Ipilan	N	S	De Lara Mining Corp.
Makambal	N	S	LBC & Greenfield Mining Co.
Mt. Kadig	N	S	Horizon Minerals & Oil Co.
Rio Tuba	P	S	Rio Tuba Mining Co.
Sablayan	N	S	Anglo Philippine Oil Corp.
Upper Volta: Boromo Greenstone	N	S	Government of Upper Volta.
Zimbabwe:			
Epoch	N	U	Trojan Nickel Co.
Madziwa	P	U	Madziwa Mines Ltd.

APPENDIX.—Properties investigated but not included in study[1] — Continued

Country and property name	Status[2]	Type of operation[3]	Owner
COPPER-COBALT PROPERTIES			
Canada: Thierry	P	U	Union Miniere, S. A. Brussels
Zaire:			
Kamoto (open pit)	P	S	Gecamines.
Musonoi	P	S	Do.
Musoshi Kensenda	P	U	Sodimiza.
Zambia:			
Kansanshi	P	S,U	Zambia Copper Consolidated Mines (ZCCM).
Luanshya	P	U	Do.
Mufulira	P	U	Do.

[1]Potential sources of cobalt not evaluated in this study include nickel laterite deposits where cobalt is being recovered within a ferronickel product or where cobalt grades are not available, or cobalt is recovered from recyling operations.

[2]P—Producing; N—Nonproducing.

[3]U—Underground; S—Surface.

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